Status Review of Southeast Alaska Herring (*Clupea pallasi*)

Threats Evaluation and Extinction Risk Analysis

Pacific herring break the surface during a spawning event in Berners Bay.

NOAA/National Marine Fisheries Service, Alaska Region
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This document is a compilation of the best available scientific and commercial data and a description of past, present, and likely future threats to the Southeast Alaska Distinct Population Segment of Pacific herring (*Clupea pallasi*). It does not represent a decision by NMFS on whether this taxon should be proposed for listing as threatened or endangered under the Federal Endangered Species Act. That decision will be made by NMFS after reviewing this document, other relevant biological and threat information not included herein, efforts being made to protect the species, and all relevant laws, regulations, and policies. The results of the decision will be posted on the NMFS web site (refer to http://www.nmfs.noaa.gov/pr/species/) and announced in the *Federal Register*.

EXECUTIVE SUMMARY

On April 2, 2007, the National Marine Fisheries Service (NMFS) received a petition from the Juneau Group of the Sierra Club to list Pacific herring in Lynn Canal, Alaska, as endangered or threatened under Section 4 of the Endangered Species Act (ESA). NMFS subsequently found that the petition presented substantial information indicating that the petitioned action may be warranted and initiated a status review. On April 11, 2008, after completing a formal status review of the best available scientific and commercial data, NMFS announced that the listing of Lynn Canal herring under the ESA was not warranted because the population did not constitute a species, subspecies, or distinct population segment (DPS). Instead, the Lynn Canal herring population was determined to be part of a larger Southeast Alaska DPS of Pacific herring. To pursue the findings of the Lynn Canal status review, NMFS initiated a status review to evaluate the extinction risk of the Southeast Alaska DPS of Pacific herring.

The key task of the status review and extinction risk assessment was to provide sufficient information to support a determination as to whether the Southeast Alaska DPS is threatened or endangered. The ESA defines the term *endangered species* as "any species which is in danger of extinction throughout all or a significant portion of its range." The term *threatened species* is defined as "any species which is likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range."

In assessing extinction risk, it is important to include both qualitative and quantitative information. The extinction risk assessment included in this document consisted of two parts: (1) a description of the five threat factors in the ESA for determining whether a species is threatened or endangered, including (A) Destruction, modification,or curtailment of habitat or range; (B) Over-utilization; (C) Disease or predation; (D) Inadequacy of existing regulatory mechanisms; (E) Other natural or man-made factors; and (2) an analysis of demographic trends relative to threats by an Extinction Risk Analysis (ERA) team composed of a panel of knowledgeable scientists. The threats section supplied qualitative information on potential risks to Southeast Alaska herring. A quantitative assessment was then made through a risk matrix method, modified from a method described in detail by Wainright and Kope (1999). This method was used to organize and summarize the professional judgment of the ERA team. In the risk matrix approach, the ERA team assessed the condition of Southeast Alaska herring populations and summarized that condition according to the following demographic risk criteria: abundance, growth rate/productivity, spatial structure/connectivity, and diversity as well as other modifying factors. These viability criteria, outlined in McElhany et al. (2000), reflect concepts that are well-founded in conservation biology and that individually and collectively provide strong indicators of extinction risk. After reviewing all the relevant commercial and biological data supplied in the threats section, the ERA team used these concepts to estimate the extinction risk of the Southeast Alaska DPS of Pacific herring based on current demographic risks.

The ERA team scores for abundance, growth rate/productivity, diversity and other modifying factors ranged from 1 to 2 with modal and median scores of 1. A score of 1 represents no or very low risk, meaning that it is unlikely that the DPS is at risk of extinction due to projected threats or trends in abundance, productivity, spatial structure, or diversity. A score of 2 represents low risk, meaning that this DPS is at risk of extinction due to trends in abundance, productivity, spatial structure or diversity; however, current threats may be altering those trends but not yet sufficiently to cause the species to be influenced by stochastic or depensatory processes. A score of 3 represents a moderate risk which means the DPS exhibits a trajectory indicating that it is approaching a level of abundance, productivity, spatial structure, and or/diversity that places its current or future persistence in question. A DPS may be at moderate risk of extinction due to declining trends in abundance, productivity, spatial structure, or diversity and current or projected threats that inhibit the reversal of these trends.

Based on data collected from the Alaska Department of Fish and Game (ADF&G) since the 1980s, the team was in general agreement that aggregations for which long-term spawning biomass data are available, have primarily either increased or fluctuated, but are not generally declining. Growth rate and productivity are also exhibiting positive trends and, based on estimates of recruitment and size-based parameters, productivity appears to be above replacement for assessed Southeast Alaska aggregations. However, the potential for periods of low recruitment that may occur when conditions do not support rapid population increases was a concern. While not all spawning aggregations are monitored, diversity also does not appear to be at risk in the population and there is currently no evidence to suggest that substantial changes or loss of variation in life-history traits, population demography, morphology, behavior or genetic characteristics is occurring.

ERA team scores for the current spatial structure/connectivity of the DPS ranged from 1 to 3 with a modal score of 1 and a median score of 1.5. While connectivity appears to be strong among stocks, concern was expressed about a possible decrease in the spatial distribution of spawning and also the proximity of some stocks to urban areas where a higher probability of habitat degradation exists.

The ERA team also completed a threats assessment by scoring the severity of current threats to the DPS as well as predicting whether the threat will increase, decrease, or stay the same in the foreseeable future. A score of 1 represents no or very low risk, meaning that it is unlikely that the factor contributes significantly to risk of extinction, either by itself or in combination with other factors. A score of 2 represents low risk, meaning that it is unlikely that the factor contributes significantly to risk of extinction by itself, but there is some concern that it may in combination with other factors. A score of 3 represents a moderate risk, meaning that it is likely that the factor in combination with others contributes significantly to risk of extinction.

The greatest risk was assigned to habitat protection followed by predation, shoreline modification and commercial fishery regulations. All threats had a low (2) to moderate (3) (habitat protection, predation) or low (2) (shoreline modification, commercial fishery regulations) median score with a range from no/very low risk to moderate risk (1, 2 – 3). With respect to habitat protection, the ERA team considered legal protection of spawning and nursery habitats as important, both currently and in the future, especially relative to increased urbanization and other stressors associated with human activity. The populations of several large predators, and consequently potential impacts on herring, were recognized to be increasing; however, it was considered likely that prey bases would shift before local extinction occurred. Concern was also expressed about the probability of increased disease prevalence with herring pounds, areas where spawning herring, either captured or naturally-occurring, are gathered to spawn on deliberately placed kelp fronds. The suspended kelp with eggs is then collected and herring returned post-spawning to the main spawning aggregation.

The ERA team then used the accumulated information to determine the DPS' overall level of extinction risk through the distribution of "likelihood points" that allow for the expression of uncertainty. The most points were assigned to the "no/low" level of extinction risk, meaning that it was considered unlikely that the DPS is at risk of extinction due to projected threats or trends in abundance, productivity, spatial structure, or diversity.

A final task included the consideration as to whether the Southeast Alaska DPS of Pacific herring was at risk of extinction throughout a significant portion of its range (SPOIR). In providing guidance for the interpretation of this phrase, NMFS and USFWS proposed a joint policy which includes these three major components:

1. If a species is found to be endangered or threatened in only a significant portion of its range, then the entire species would be listed as endangered or threatened.
2. The range of a species is "significant" if its contribution to the viability of the species is so important that without that portion, the species would be in danger of extinction.
3. The range of a species is considered to be the general geographical area within which the species, including all or any part of its life cycle, can be found at the time the status determination is being made.
   Lost historical range would not constitute a significant portion of a species' range (and a species cannot be listed solely on the basis of loss of historical range), but the causes and consequences of loss of historical range on the current and future viability of the species must be considered and are an important component of determining the risk of extinction.

According to these criteria, the ERA team did not find any portion of the range within the DPS that would warrant a different level of extinction risk. The team concluded that the Southeast Alaska DPS of Pacific herring is not at risk of extinction throughout all or a significant portion of its range.

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1.0 Introduction

On April 2, 2007, the National Marine Fisheries Service (NMFS) received a petition from the Juneau Group of the Sierra Club to list Pacific herring (*Clupea pallasii*) in Lynn Canal, Alaska, as endangered or threatened under Section 4 of the Endangered Species Act (ESA), and also to designate critical habitat for Lynn Canal herring concurrently with any listing. NMFS subsequently found that the petition presented substantial scientific and commercial information indicating the petitioned action may be warranted [72 FR 51619; Sept. 10, 2007] and initiated a status review. On April 11, 2008, after completing a formal status review of the best available scientific and commercial data, NMFS announced that the listing of Lynn Canal herring under the ESA was not warranted because the population did not constitute a species, subspecies, or distinct population segment (DPS). Instead, the Lynn Canal herring population was determined to be part of a larger Southeast Alaska DPS of Pacific herring [73 FR 19825; April 11, 2008]. Therefore, to pursue the findings of the Lynn Canal status review, NMFS initiated a new status review to evaluate the extinction risk of the Southeast Alaska DPS of Pacific herring.

2.0 Status Review Process

Two key tasks are associated with conducting a status review under the ESA. The first task is to delineate the taxonomic group under consideration as a distinct species; the second task is to then assess the risk of extinction of the species under consideration.

2.1 Species Determination

To be considered for listing under the ESA, a group of organisms must first constitute a "species". For the purposes of the ESA, Congress has defined a species as "any subspecies of fish or wildlife or plants, and any distinct population segment of any species of vertebrate fish or wildlife which interbreeds when mature" [16 U.S.C. 1532(16)]. Guidance on what constitutes a distinct population segment (DPS) is provided by the joint NMFS-US Fish and Wildlife Service interagency DPS policy [61 FR 4722; February 7, 1996]. In order to be classified as a DPS, a population must meet two criteria – discreteness and significance. A population, or group of populations, must first be "discrete" from other populations and then "significant" to the taxon (species or subspecies) to which it belongs. According to the joint DPS policy, a population segment may be considered discrete if it satisfies either one of the following conditions: (1) it is markedly separated from other populations of the same biological taxon as a consequence of physical, physiological, ecological or behavioral factors (quantitative measures of genetic or morphological discontinuity may provide evidence of this separation); or (2) it is delimited by international government boundaries across which there is a significant difference in exploitation control, habitat management or conservation status. If a population is determined to be discrete, the agency must then consider whether it is significant to the taxon to which it belongs. When evaluating the significance of a discrete population, the following is considered: (1) persistence of the discrete population in an unusual or unique ecological setting for the taxon; (2) evidence that the loss of the discrete population would cause a significant gap in the taxon's range; (3) evidence that the discrete population segment represents the only surviving natural occurrence of a taxon that may be more abundant elsewhere outside its historical range; or (4) evidence that the discrete population has marked genetic differences from other populations of the species. The process and foundation upon which the Southeast Alaska Pacific herring DPS was established is described in Section 3.0.

2.2 Extinction Risk Assessment

The second key task of the status review is to conduct an extinction risk assessment to provide sufficient information to support a determination whether the petitioned species is threatened or endangered. The ESA defines the term *endangered species* as "any species which is in danger of extinction throughout all or a significant portion of its range." The term *threatened species* is defined as "any species which is likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range." A species shall be listed if the best scientific or commercial data determines that if the species is either threatened or endangered because of one or more of the following factors:

1. the present or threatened destruction, modification, or curtailment of its habitat or range;
2. overutilization for commercial, recreational, scientific or educational purposes.
3. predation and disease;
4. the inadequacy of existing regulatory mechanisms;
5. other natural or man-made factors affecting its continued existence.

[50 CFR 424.11(c)].

An evaluation of these threats as well as an extinction risk analysis can be found in Sections 6.0 and 7.0 of this report.

3.0 Pacific Herring

Pacific herring are a small, mobile, planktivorous forage fish belonging to the Clupeidae family. The range of Pacific herring includes coastal regions along the eastern and western Pacific, with a northerly range extending into the Beaufort Sea and Arctic Ocean (Hart 1973; Mecklenburg et al. 2002). Pacific herring are also found in many large and small aggregations throughout the Alexander Archipelago. Habitat requirements for the species in Southeast Alaska are diverse and partially a function of life stage. The most visible, and crucial, event in the herring life cycle is spawning, which generally occurs at predictable times (typically in the spring/early summer) and in predictable locations (Hay and Outram 1981). During spawning events, adult herring congregate along shorelines protected from ocean surf. Within these established spawning grounds, female herring deposit eggs onto a variety of different substrate types, including eelgrass, kelp, rockweed and other seaweed as well as on inorganic material such as rocks or pilings (Hart 1973). Male herring then fertilize the eggs externally.

Following the spawning event, eggs usually hatch to a larval stage in about 2 – 3 weeks, depending upon the water temperature (Outram 1955). Within a week of hatching, larvae must begin feeding to ensure survival, although they may be passively advected away from feeding areas (McGurk 1984). Once the larvae become nektonic, they move to favorable habitats where they metamorphose to juveniles and form schools. Preferred habitat for adult and juvenile herring includes a variety of nearshore habitat types, such as bedrock outcrops, eelgrass, kelps, and sand-gravel beaches (Johnson and Thedinga 2005). Juveniles begin recruiting to the adult population at age 3 (Williams and Quinn 2000; Hay et al. 2001). Adults live in schools that undergo diurnal and seasonal movements. Seasonally, adult herring tend to migrate between summer feeding areas on shelf waters to overwintering areas, often in deep, protected nearshore water, and then to spawning locations (Hay et al. 2001).

Herring are considered a keystone species in Southeast Alaska, serving as a vital link between lower trophic levels, including crustaceans and small fish, and higher trophic levels, including a diversity of predators such as marine mammals, birds, invertebrates and piscivorous fish. Natural mortality of herring is significant throughout all life stages, primarily from predation, disease and unfavorable environmental conditions. Herring are also commercially fished in Southeast Alaska.

Further information concerning the biology and ecology of herring in Southeast Alaska may be found herein or in the document delineating the DPS by Carl et al. (2008).

4.0 Establishment of Southeast Alaska Pacific Herring DPS

Several sources of data were considered in evaluating the DPS structure of Southeast Alaska herring populations. This information included: geographic variability in life-history characteristics, physiology, and morphology; ecosystem and oceanographic conditions; spawn timing and locations, tagging and recapture studies that would indicate the extent of migration and intermingling among stocks; and studies of genetic differentiation among stocks that would suggest some degree of reproductive isolation. After analyzing the best available scientific and commercial information, the Southeast Alaska DPS was determined to extend from Dixon Entrance northward to Cape Fairweather and Icy Point and includes all Pacific herring stocks in Southeast Alaska (Fig.1). The process of the DPS determination and findings were included as part of the Lynn Canal Status Review document (Carls et al. 2008).

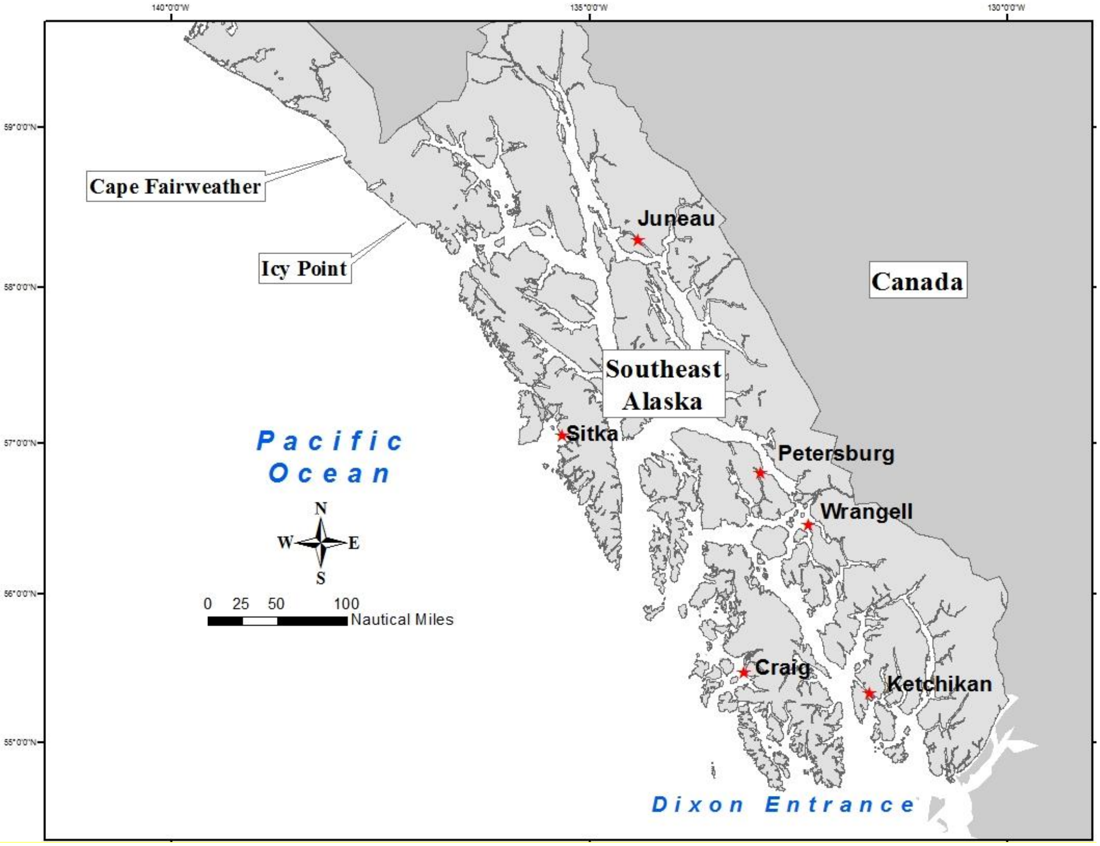


Figure 1. Geographic boundaries of the Southeast Alaska Pacific herring DPS (Carls et al. 2008).

The following information on discreteness and significance was the basis for the Southeast Alaska DPS delineation.

4.1 Discreteness

The delineation of the southern boundary is based on genetic differences between herring in Southeast Alaska and those in British Columbia, as well as differences in recruitment and average weight-at-age, parasitism, spawn timing and locations, and the results of tagging studies conducted in British Columbia. The northern boundary is defined by physical and ecological features that create migratory barriers, as well as large stretches of exposed ocean beaches that are devoid of spawning and rearing habitats (Carls et al., 2008).

4.2 Significance

Given the large scope of this geographic area and the large number of stocks found throughout Southeast Alaska, NMFS determined that the Southeast Alaska Pacific herring population is significant to the taxon as a whole. Specifically, the Southeast population exists in a unique ecological setting, and the extirpation of this population of Pacific herring would result in a significant gap in the range of the taxon (Carls et al., 2008).

The BRT also recognized the possibility that there may be subdivisions within the Southeast Alaska DPS. Data released since the DPS determination may support this possibility. A study assessing whether the Lynn Canal stock is genetically distinct from other eastern Gulf of Alaska herring found that the genetic structure of samples from the fjord system of Berners Bay and Lynn Canal was significantly different from samples taken from Sitka Sound/outer coast herring. Hobart Bay, considered an interior water body on a main waterway bisecting southeast, shared genetic features of both, while Hoonah Sound herring were found to be genetically distinct from Lynn Canal and Berners Bay herring (Wildes et al. 2011) with a fatty acid signature that also differed from other areas tested in Southeast (Otis et al. 2010). Although a larger, multi-year sampling was recommended, results also showed genetic differences between samples from Southeast Alaska and Prince William Sound. Another study using microsatellites to assess the genetic population structure of herring in British Columbia and adjacent regions found differentiation between herring that spawned in more inland waters and those that spawned in more seaward locations, a difference possibly related to life history, because resident herring spawn in mainland inlets and adjacent inland waterways while migratory herring spawn in coastal areas and move to offshore summer feeding grounds. While the same study found distinctions between herring of California, Washington, and subgroups of herring in British Columbia, primarily due to spawn timing and geographic isolation, less differentiation existed between Southeast Alaska and British Columbia. Very little differentiation was noted between the Southeast Alaska herring stocks, which included: (1) combined samples from Mary Island and Kirk Point; (2) combined samples from north and south Sitka Sound; and (3) samples from Seymour Canal (Beacham et al. 2008).

Although these studies indicate that environmental differences may have reduced the gene flow in some regions of southeast Alaska and corresponding adaptions have occurred in herring in outer coastal as compared to interior waterways, the data do not contradict the DPS delineation.

5.0 Extinction Risk of the Southeast Alaska Herring DPS

5.1 Approach

Following the DPS delineation is the consideration of a possible listing determination as either threatened or endangered under the ESA. Section 3 of the ESA defines an endangered species as “any species that is in danger of extinction throughout all or a significant portion of its range.” A threatened species is defined as “any species which is likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range.” The determination of whether a species should be listed as endangered or threatened must be based solely on the best scientific and commercial data available, after taking into consideration conservation measures that are in place or certain to be implemented or effective.

The extinction risk portion of a status review must be of sufficient scope and depth for NMFS to adequately determine whether the DPS is in danger of extinction or likely to become so in the foreseeable future throughout all or a significant portion of its range.

There are many possible quantitative and qualitative approaches to assessing extinction risk. This extinction risk analysis for potential ESA listing includes the following:

a. An analysis of the five ESA Section 4(a)(1) threat factors. The threats analysis is organized around the bulleted "factors" A through E in Section 4(a) of the ESA, commonly referred to as the "five listing factors". These factors, representing principle, external mechanisms that can cause populations to decline to extinction, are as follows:
    i. the present or threatened destruction, modification or curtailment of its habitat or range;
    ii. over utilization for commercial, recreational, scientific, or educational purposes;
    iii. disease or predation;
    iv. the inadequacy of existing regulatory mechanisms; or
    v. other natural or manmade factors affecting the species' continued existence.

In other words, when considering the "weight of the evidence" (the presumed legal basis for ESA decision-making under uncertainty), *all extinction risk factors* for which information is available must be included in the evidence. Thus, what is traditionally called "five-factor analysis" is better described as "full-factor analysis," although endangerment may stem from only one or a few factors.

b. An analysis of demographic trends relative to threats. Threats to a species' long-term persistence are manifested demographically as trends in abundance, productivity, spatial structure, diversity and/or other relevant factors. Trends in these parameters provide the most direct indices or proxies of extinction risk.

The qualitative relationship between demographic trends, and population thresholds is described in Figure 2.

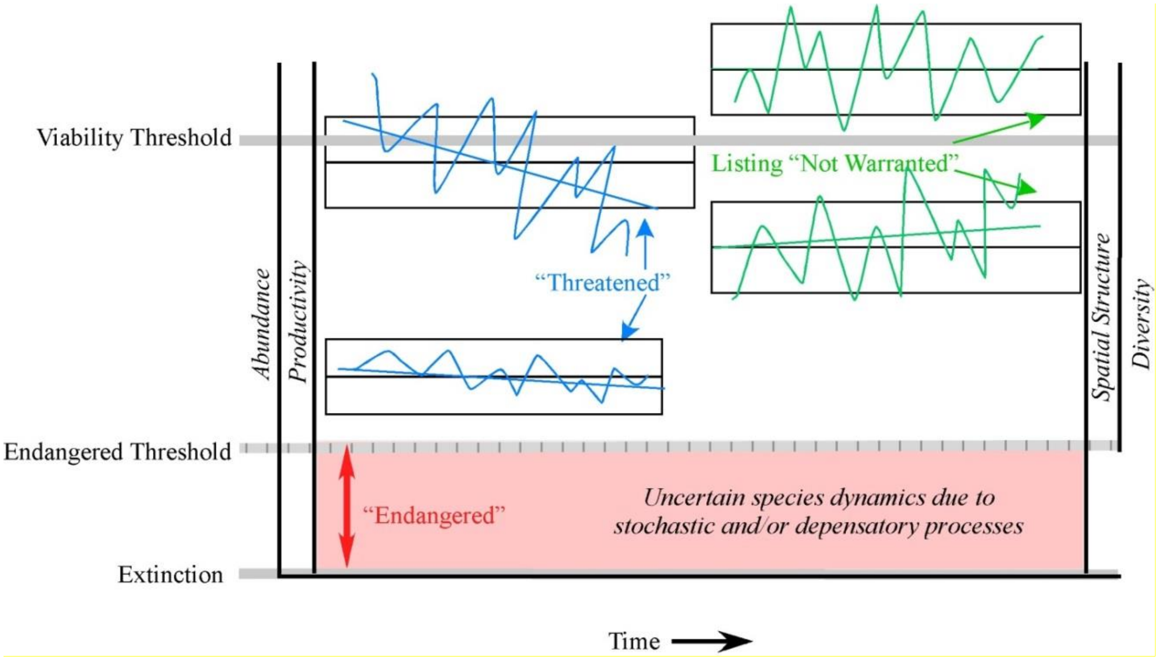


Figure 2. Schematic representation of "endangered" and "threatened" status evaluated relative to a qualitative endangered threshold.

The status of endangered species is at or below the endangered threshold where the species' dynamics are dominated by stochastic and/or depensatory processes, and the overall trajectory of the species is expected to be towards extinction. "Threatened" species exhibit a trajectory indicating that they are likely to reach the endangered threshold within the foreseeable future. A species that is currently below viable abundance levels may not warrant listing as "threatened" if it exhibits robustly positive productivity trends and sufficient habitat remains accessible. The extinction risk of species is assessed in terms of demographic risks to its abundance, productivity, spatial structure and diversity (McElhany et al. 2000; Nammack et al. 2013).

Herring in southeast Alaska have been grouped into a single DPS that spans the geographical area from Dixon Entrance to Cape Fairweather and Icy Point. It follows that members of the DPS should be considered as a single entity and this is how information was generally presented and considered in this document. However, local seasonal aggregations (classified as spawning stocks by ADF&G and treated as synonymous with stock in this document) were also considered both singly and collectively, most often with respect to quantitative data analysis. This approach was in response to the following factors:

- The biomass of herring in Sitka Sound is almost an order of magnitude greater than other spawning stocks. The Sitka stock could potentially drive results of a quantitative assessment for the whole DPS. While considering each stock separately generally proved to be too unwieldy, compiling data from all of the smaller stocks (less Sitka Sound) allowed potentially different population dynamics to be addressed.

- While Southeast Alaska Pacific herring are considered a single DPS, the ESA requires assessment of extinction risk “throughout all or a significant portion of its range” (SPOIR). Consequently, some analyses of data concerning the different components of the DPS were required. A matrix of abundance (Appendix A, A.1 – A.9), as one of the most significant and most consistently available data types, was used to assess extinction risk of individual stocks across the SPOIR.

- Herring in Southeast Alaska likely fit the definition of a metapopulation, which, while fluid, may be viewed as” a system of discrete local populations, each of which determines its own internal dynamics to a large extent, but with a degree of identifiable and nontrivial demographic influence from other local populations through dispersal of individuals” (Kritzer and Sale 2004). As a metapopulation, considering the status of local aggregations can, in part, help in understanding the health of the population as a whole.

- Evidence suggests that herring from the outer coast, e.g., Sitka Sound, are subject to different environmental factors than herring from interior waters. These factors may, in turn, influence the characteristics of local aggregations (Section 4.2). Analyzing data from individual aggregations separately potentially allows these characteristics to be addressed.

After assessing the number and magnitude of threats as well as current population trends, the issue is whether the Southeast Alaska DPS of Pacific herring is experiencing processes leading towards possible extinction.

5.2 Marine Extinction

It was not until the end of the 20th century that the concept of marine extinction started to receive serious consideration within the scientific community. Before that time, and for centuries, the ocean was simply thought to be too vast and its inhabitants too numerous to be subject to significant damage from any source. Although this long-held belief has since shifted to a position of greater concern as well as increased recognition for extinction potential, the concept of marine extinction still faces numerous challenges. Despite a growing knowledge base, and some solid evidence, the exact nature and number of marine extinctions has been difficult to characterize. At least 133 marine species are thought to have become extinct on a local, regional or global level, but the true number is difficult to quantify (Dulvy et al. 2003). One of the primary problems in defining marine extinctions is that detecting extinction of non-air breathing animals is extremely challenging (Roberts and Hawkins 1999), often accompanied by an uncertainty of taxonomic status with an undefined point of when the last individual is gone (Carlton 1999). Consequently, little is known about the extinction risk of most marine species and significant debate has arisen regarding methods of extinction risk assessment.

5.3 Parameters of Vulnerability

Vulnerability to extinction depends upon the number and magnitude of extrinsic threats as well the intrinsic coping ability of the species in question. Species most vulnerable to perturbation are those with limited compensatory mechanisms and scientists have identified a suite of traits in fish considered most prone to extinction. Grouping species by resilience as indicated by these biological correlates has been suggested as an initial screening procedure to identify species at particular risk (Powles et al. 2000; Dulvy et al. 2004; Reynolds et al. 2005).

Among widespread, commercially valuable marine fish, those considered most at risk have typically been large, slow growing and late maturing species, often found within restricted habitats or small ranges (Jennings et al. 1998; Musick 1998; Sadovy 2001). However, this may be true only on a regional basis; globally, species with fast life histories have at least as high a probability of extinction per stock as larger, more slowly growing species (Pinsky et al. 2011). Many marine species are also thought to possess some degree of “extinction resilience” through traits such as high fecundity, greater natural fluctuations in abundance and intrinsically faster rates of recovery, although these assertions have been questioned (Musick 1999; Powles et al. 2000; Hutchings 2001). For example, high fecundity, defined as the quality of producing young in great numbers (up to 134,000 eggs have been reported in Pacific herring; Katz 1948), has long been perceived as a predictor for resilience and protection against extirpation. However, evidence has shown that fecundity is actually a poor predictor of either vulnerability or resilience for recovery (Myers et al. 1999; Rickman et al. 2000; Denney et al. 2002). From an evolutionary point of view, natural processes may select for a reproductive strategy that allows an individual to replace itself. Fecundity, on the other hand, is a reproductive strategy that allows an individual to produce more offspring than necessary to replace itself and may be a factor to maintain fitness at equilibrium (Hutchings 2000) and not necessarily a characteristic that offers protection against surplus threats. Regarding natural fluctuations in abundance, many stocks of small pelagic fishes may undergo wide fluctuations, and up to 10-fold abundance swings are not uncommon. Stocks have also collapsed and subsequently recovered from near extirpation. However, distinguishing natural from fishing-induced fluctuations in these populations can be difficult. Recruitment variability in marine fish has not been found to exceed that of anadromous counterparts (Mertz and Myers 1996), and the spawning component of marine fish does not experience a greater frequency of decline than that of non-marine fishes, including freshwater and anadromous species (Hutchings 2001). In general, it has been shown that temporal population fluctuations in adult fish are not greater than in birds or terrestrial mammals (Hutchings 2001a; Dulvy et al. 2003). There is also little empirical support for the assumption that recovery from prolonged reductions in abundance occurs more quickly in marine than in non-marine species. Based on data of decline from 283 stocks of both freshwater and marine species of fish, population resilience was similar between the two groups, although the incidence of full recovery among anadromous populations was more than twice that of marine fish and further decline was twice as probable in marine species (Hutchings 2001).

As a relatively small, fast- growing and early-maturing fish, clupeids do not share the biological correlates noted in fish at greatest risk of extinction and, in fact, appear to exhibit greater resiliency than many other families of commercially exploited marine fish. After prolonged decline, clupeids are more likely to recover to previous population sizes, although whether this perceived resilience is due to life history characteristics or the fishing technology specific to clupeids is unknown (Hutchings 2000, 2001a). Despite this increased recovery rate, among 56 populations of clupeids, 73% experienced historic declines of 80% or more (Hutchings and Reynolds 2004) and have been eliminated from parts of their range in the past century (Dulvy 2003).

5.4 Other Herring Stocks

Herring occur along the northern coasts of the Atlantic and Pacific Oceans as well as in parts of the Arctic. Although there are many biological differences between herring stocks, including timing and location of spawning and age at first maturity, sufficient similarities exist among stocks to warrant attention to potential extinction events, and its causes, within the group. In all systems, herring serve as both predator, mainly of zooplankton, and prey. As a prey species herring are consumed by "nearly all animals large enough to eat them" (Hay et al. 2001a), including marine mammals, birds, piscivorous fishes and invertebrates. Herring have been used for human food and commerce for centuries, but it was only been within the last 100 years that herring have been subject to intense commercial fishing. During this time, most of the stocks have displayed marked fluctuations in abundance, and most have collapsed at least once, with the most severe declines preceded or accompanied by intense fishing. In the 1960s, for example, the combination of advances in fishery technology and difficult environmental conditions resulted in the collapse of many stocks, causing this to be called the "decade of the collapses" (Beverton 1990). In the majority of instances, stocks recovered when fishing decreased or stopped, with the temporal duration of the periods of collapse generally lasting a decade or longer. However, extinction risk involves the probability that a collapsed stock will recover as well as the probability of abundance moving to zero (Hutchings 2001a; Reynolds et al. 2005). The former may be reduced if changes in biological structure or ecosystem prohibit full recovery (Beverton 1990). More than fifty years ago, one of the world's largest stocks of herring, the Hokkaido-Sakhalin stock along the western Pacific, failed to recover from a gradual decline, leading to the disappearance of spawning fish (Hay et al. 2001a). Causes of that decline likely included both intense fishing pressure during a period of natural decline (Hay et al. 2001a) and changes in sea surface temperatures (Hay et al. 2001a; Nagasawa 2001). Although herring appear to be more resilient than many other fish species, they are not immune to prolonged or possibly permanent collapse.

6.0 Threats

In the following section, each of the five "factors for decline" is examined relative to the current status of Southeast Alaska Pacific herring. Historic data is included to provide context in describing trends relative to the present.

6.1 Habitat Modification

In analyzing 82 species and subspecies of fish vulnerable to extirpation in North American waters, habitat degradation was deemed second only to life history limitations as a risk factor (Musick et al. 2000).

6.1.1 Life History: Habitat and Mortality

Pacific herring utilize much of southeastern Alaska waters as habitat. In characterizing the distribution and habitat of the 50 most abundant fish species in shallow nearshore waters, Pacific herring were one of the most abundant. Herring, and juvenile herring in particular, were captured in a variety of nearshore habitat types throughout Southeast Alaska, such as bedrock outcrops, eelgrass, kelps and sand-gravel beaches (Murphy et al. 2000; Johnson and Thedinga 2005). Other physical and biotic components, such as temperature, salinity and other dominant fish species, also differ between occupied habitats (Carls et al. 2008). Consequently, habitat modification and subsequent impacts to herring may be very specific according to the spatial and temporal characteristics of each life stage.

Spawning of herring in Southeast Alaska generally occurs from March to June. With the spring increase in water temperature and duration of daylight, adult herring move from overwintering habitat to shallow, protected inshore areas such as inlets, sounds, bays and estuaries to spawn. Male herring release sperm into the water and induce females to deposit eggs in intertidal and subtidal zones between the high tide line and 15 m in depth. Eggs are laid on a variety of silt-free vegetation, sand or rock (Haegele and Schweigert 1985), but may also be laid on artificial substrate such as dock pilings. Physical forces that cause egg mortality include wave action, predation, and smothering due to heavy deposition density (Hourston and Haegele 1980; Rooper et al.1999; Norcross and Brown 2001). Other physical processes in the spawning habitat, including salinity and temperature, may also influence viability (Alderdice and Hourston 1985).

After a 10 to 12 day incubation period, newly hatched larvae are retained or passively advected by currents to favorable or unfavorable nursery areas (Lasker 1985; Carls et al. 2008), such as protected inside waters or offshore currents, respectively. Yolk-sacs provide nutrition for 10-14 days and the larvae must begin feeding (Hart 1973). From 18 to 36% of first feeding larvae may starve (McGurk 1984). Mortality during this drifting stage may result from starvation, predation and off-shore dispersal (Hourston and Haegele 1980; McGurk 1989). In Sitka Sound, mapping of herring larval distribution between 1989 and 1990 suggested that that the north end of the Sound was a retention area and that the distribution of spawning sites may have been the result of enhanced survival due to retention in the north (Haldorsen and Collie 1990).

Larvae that survive to become nektonic metamorphose to the juvenile stage in late July and August. By the end of the summer most juveniles are found in edge-zone bays and fjords. In these nursery areas, food availability, competition, predation and disease may affect the survival of juvenile herring (Norcross and Brown 2001).

Combining stage specific survival in Prince William Sound yielded a range in survival estimates of 1 to 6500 juvenile herring per 1 million eggs, with late larval and early juvenile herring most susceptible to mortality. Basic components in early life history survival include spawning amount, location, and timing; loss and predation of eggs; direction of larval dispersion and timing of larval entry into bays and fjords; food, predation, and temperature in nursery areas; condition and size of juveniles; and winter duration and water temperature (Norcross and Brown 2001).

6.1.2 Anthropogenic Habitat Modification

No overt wide-scale habitat modification currently threatens the DPS of Southeast Alaska herring (except perhaps climate change as addressed in Sec. 6.5). However, habitat modification may also occur on a localized scale such as with spreading urbanization, or on a lesser, but cumulative and chronic basis with increased marine pollutants, traffic and noise.

6.1.2.1 Shoreline modification/ urbanization

All life stages of Pacific herring use near-shore marine and estuarine habitats and human activity in these areas may decrease, modify or preclude herring use. Human habitation and activity may modify surrounding habitats in several ways. The construction of permanent and temporary structures may result in physical disruption, noise, and pollution in marine communities as well as associated increases in marine transportation, industry, and recreation.

Marine construction can lead to the physical destruction of sensitive ecosystems and bottom-dwelling aquatic communities (EPA 2010). Jetties and breakwaters, for example, may affect marine habitat function for herring by inhibiting migration and disrupting movement, blocking or altering access to nursery areas, modifying food production and feeding; altering or covering shallow vegetated and beach habitats used for spawning, attracting predators and changing physicochemical properties (Turner et al. 1997; Williams and Thom 2001). In December of 2012, a massive die-off of more than 30,000 tons of herring in Kolgrafafjordur, a small fjord in Iceland, was thought to be the result of low oxygen due to the construction of a landfill and bridge across the fjord (AND 2012). In Southeast Alaska, the construction of permanent structures may result in the loss of eelgrass or kelp, which is likely important for all Southeast Alaska herring life stages. Decreased abundance of herring in areas with multiple inter and sub-tidal structures, such as in Auke Bay, may be associated with the loss of habitat features such as eelgrass. Juvenile herring appear to school in these vegetation types and therefore destruction of eelgrass or kelp beds may affect fish in large numbers (Johnson et al. 2003).

Along with shifts in the biotic composition of a marine ecosystem, urbanization and shoreline modification may also change physical forces such as waves and currents. The construction of the Sitka Harbor breakwaters, for example, decreased water circulation and increased silt deposition, which may have reduced biomass of herring spawn inside the harbor (Larson and Hebert 1998). Ten years after construction, algal colonization on both sides of the breakwaters was extensive, except for the absence of *Macrocystis* kelp, an important substrate for herring spawn (Brockman and Grossman 2005), inside the harbor. Conversely, physical forces may exacerbate the impacts of on-shore anthropogenic activity, including the addition of soil runoff and anthropogenic waste into marine environments with increased precipitation.

Of the shoreline catalogued in the NOAA ShoreZone Coastal Habitat Mapping Program, which covers the shore from the zero-meter or lower summer low tide to the supratidal “splash” zone, only 1.4% of the mapped units showed anthropogenic activity, such as pilings, ports, seawalls, cable/pipelines and breakwaters (Fig. 3). Man-made structures along the water’s edge without features that extend into the tidal or splash zone are not included.

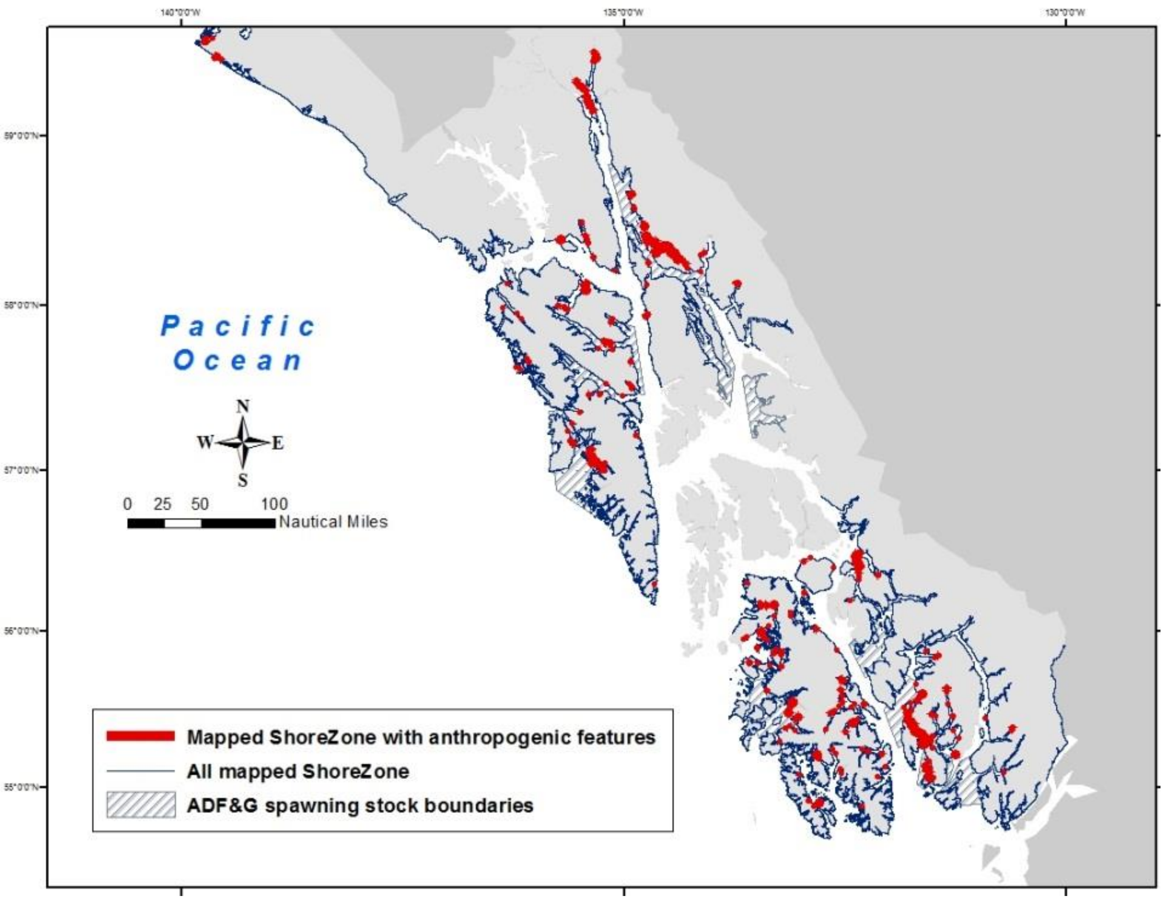


Figure 3. Mapped ShoreZone with anthropogenic features in Southeast Alaska.

A comprehensive list of projects affecting marine or near-shore environments in Southeast Alaska is not readily available. However, a sample of projects located within three miles of herring spawning areas for which the Army Corps of Engineers (ACOE) has opened the permitting process is illustrated in Figure 4.

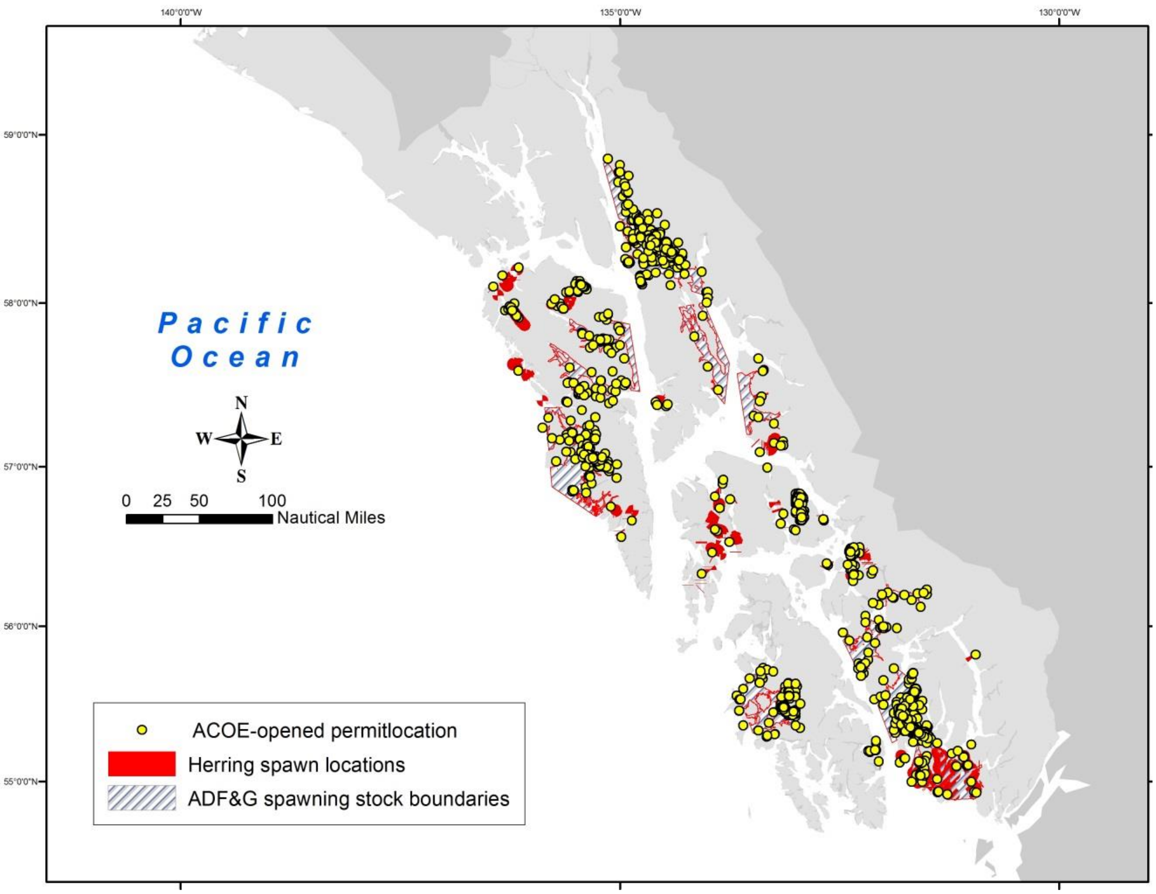


Figure 4. Sample of projects with ACOE-opened permits located within 3 miles of herring spawning locations (Data courtesy ACOE).

Although the extent of information specific to the individual projects is limited, projects include activities such as residential fill, dock construction, piling replacement and placement of a float house. It is apparent that there are few areas of recorded herring spawn that have not been subject to anthropogenic activity.

6.1.2.2 Invasive species

Human activity may also indirectly lead to habitat degradation through the introduction of invasive species. An invasive species that currently poses a threat to herring habitat in Sitka is *Didemnum vexillum*, a colonial tunicate found in Whiting Harbor near Sitka in 2010 (Cohen et al. 2011). If left unchecked, *D. vexillum* is likely to increase spatially and temporally. Spread of the species is of concern to benthic marine habitats because it attaches to firm substrates, rapidly overgrows other species, tolerates a range of temperatures, has no significant predators, and spreads by colony fragmentation (Valentine et al. 2007). Besides smothering infaunal organisms, *D. vexillum* secretes an acidic toxin that discourages settlement upon it by other organisms. The tunicate may deter larval settlement of shellfish (Morris et al. 2009). It is also suspected, although not proven, that *D. vexillum* may be toxic to herring eggs and deter future herring spawning (L. Shaw, personal communication, 11/9/2011). Vessel traffic and aquaculture are considered the main vectors for spreading (Bullard et al. 2007) and the potential exists for *D. vexillum* to invade and colonize other habitats throughout Southeast Alaska.

Urbanization and community growth may also significantly alter the quality of the marine environment through the introduction of pollutants as well as through increased marine activity, such as vessel traffic and noise. The volume of pollutants and marine activities that may impact marine habitats is, in part, a function of the human population. In 2012, the population of Southeast Alaska was 74,423, which includes growth an all major communities in the region except for Skagway and Yakutat (ADLWD 2012). While the human population in Southeast Alaska is relatively small, the number of summer visitors adds significantly to human activity in the region. From May to September of 2006, for example, Southeast Alaska received 1.2 million visitors. The majority of these visitors (82%) were in the region for vacation/pleasure, which includes substantial involvement in marine activities such as fishing and whale watching (ADCCED 2007). Therefore, the potential for pollutants entering the marine environment as well as increased vessel traffic and noise may also result from a significant seasonal increase in the population.

6.1.2.3 Pollution

Pollution arises from a wide range of sources. In Alaska, nonpoint source pollution is the largest source of water quality problems. Common sources of nonpoint source pollution include urban runoff, road construction, timber harvests, off-road vehicles, boats and marinas, septic systems, agriculture, and people damaging shorelines when angling or building structures (ADEC 2012). Water pollution from boating and dock systems, for example, may be linked to several sources, including poorly flushed waterways, boat maintenance, sewage discharge from boats, storm runoff from parking lots and the physical alteration of shoreline and aquatic habitat during construction and operations (EPA 2010). The associated environmental impacts may also vary, including increased water toxicity, increased pollutant concentrations in aquatic organisms and sediments, increased erosion rates, increased nutrients leading to an increase in algae and a decrease in oxygen (eutrophication), changes in microalgal diversity, introduction of foreign species (Walker and Kendrick 1998), and high levels of pathogens (EPA 2001). Pollutants associated with shoreline modification and urbanization include sediments, oil, grease and toxic chemicals from motor vehicles, pesticides and herbicides, pathogens, road salts, particulate and dissolved, heavy metals, thermal pollution and litter (EPA 2003; Caltrans 2010). Many of these substances may adversely affect the marine environment through reduced fish diversity and degraded aquatic habitat. Following are examples of contaminants in the marine environment that may affect herring:

- Creosote: creosote includes up to 85% polyaromatic hydrocarbons (PAH) and functions as wood preserver and pesticide. In a laboratory setting, certain levels of creosote lead to skeletal abnormalities and reduced swimming ability, although the creosote dosage to fish in a natural marine setting was unknown (Duncan and Carls 2012). Other studies have found that exposure to creosote treated wood reduced herring embryonic development and hatching rate by 90% and all of the exposed, but hatched, larvae exhibited morphological abnormalities (Vines at al. 2000).
- Sewage sludge: exposure of herring eggs to sewage sludge at concentrations ranging from .01 to 1% , whether due to effects of variations in oxygen

concentration, metals, ammonia, pH or other toxicants, resulted in significant and reproducible toxic effects to embryo viability, time of hatching, mortality during hatching, post-hatch larval survival and larval feeding (Costello and Gamble 1992).

- Copper: exposure to copper, primarily found in municipal waste waters, effluents from power plants, and antifouling paint on boats (Johnson and Gonzalez 2005; Parks et al. 2010), reduced growth and increased mortality in herring larvae and embryos (Rice and Harrison 1978).
- Oil: exposure of Pacific herring to components of oil, probably some of the most ubiquitous contaminants in the marine environment was extensively studied following the 1989 *Exxon Valdez* oil spill in Prince William Sound. Oil may affect the reproductive potential in adult fish (Kocan et al. 1996a) and cause developmental and cytogenetic effects on embryos and larvae (Kocan et al. 1996b; McGurk and Brown 1996; Norcross et al. 1996; Marty et al. 1997; Carls 1999). Marine substrates oiled by spills may become sources for toxic components of oil (Short et al. 2003), which may persist and cause chronic effects even at low exposures (Peterson et al. 2003). Oil spill effects on herring depend upon many complex variables including population dynamics, season, location, local ecology, hydrographic conditions and large-scale ecological processes (Carls et al. 2002). Toxicity of some oil components, for example, may increase with exposure to light (Barron . 2003).

  Of the 6,518 reports to the US Coast Guard between 1990 and 2012 concerning marine incidences in Southeast Alaska, 487 were reports of large vessel mishaps including collision/allusion, grounding, fire, flooding, material failure and oil spill. Of these reports, 117 were for oil spills not connected to another event and most were for minor spills (Nuka 2012)

Regarding water quality, the Clean Water Act (CWA) mandates that each state develop a program to monitor and report on the quality of its surface and ground waters. The CWA includes sections that require the quality of all water bodies to be characterized [CWA 305(b)] and that states list any impaired water bodies that do not meet water quality standards [CWA 305(d)]. Generally, water bodies are designated to categories by the degree to which water quality goals are attained. Approximately 99.9% of Alaska's waters are classified in Category 1 where all water quality standards for all designated uses are attained. Category 2 water bodies are those in which some water quality standards for the designated uses are attained, but data and information to determine whether the water quality standards for the remaining uses are attained are insufficient or absent. Category 4 water bodies are those determined to be impaired but not needing to meet a total maximum daily load (TMDL) or recovery plan. Category 5 water bodies are those in which water quality standards for one or more designated uses are not attained and the water body requires a TMDL or recovery plan (ADEC 2010a). Figure 5 shows impaired water bodies from Categories 2 – 5 in Southeast Alaska relative to herring stock boundaries. (N.B.: Ward Cove, in Ketchikan was one of the sites where a VEN epizootic, associated with low dissolved oxygen, occurred in 1985). In Southeast Alaska, the most common pollutants associated with impaired water bodies include bark and woody debris from log transfer and storage facilities, pulp residues, logs, bark and woody debris, low dissolved oxygen, toxicity due to wood decomposition by-products and sediment associated with the timber industry or pulp mills, various metals associated with the mining industry and seafood residues and processing wastes associated with seafood processing (Table 1).

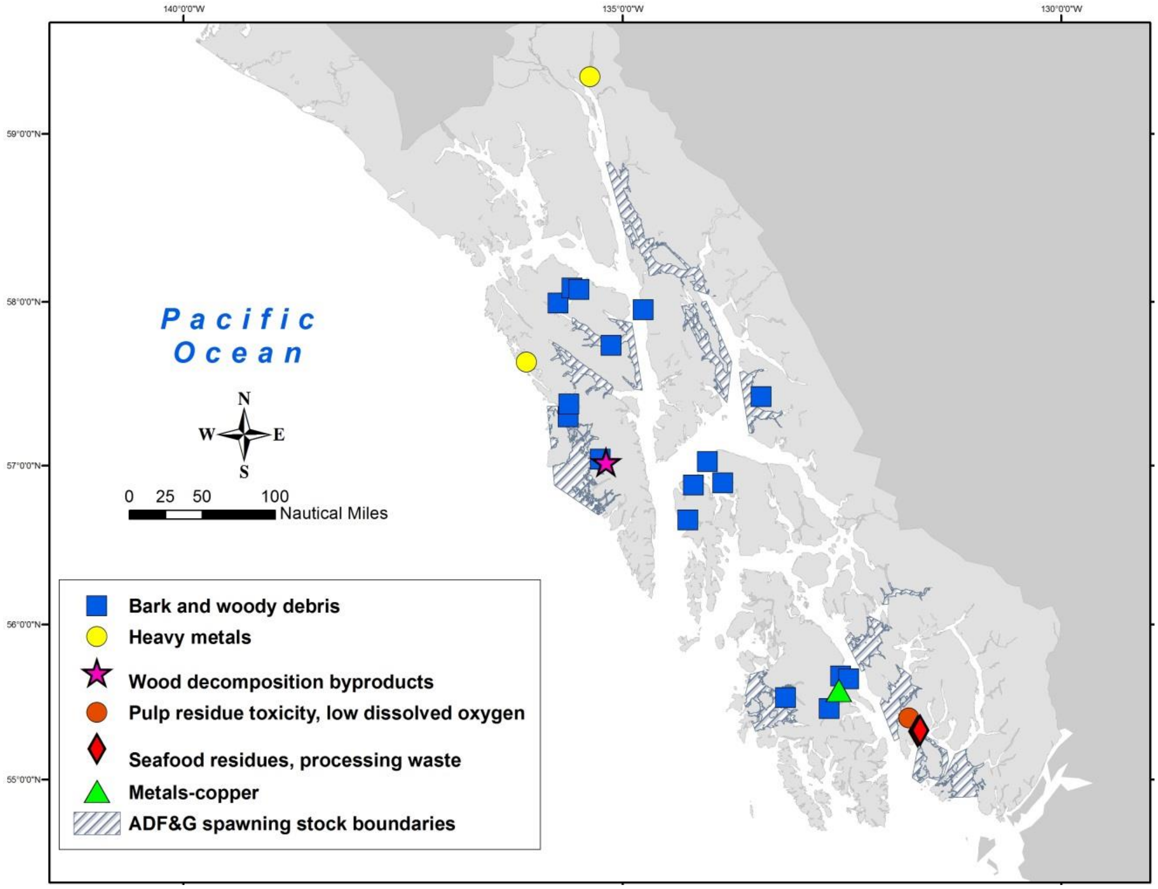


Figure 5. Location of impaired water bodies in Southeast Alaska relative to herring stock boundaries (ADEC 2010a).

Waterbody	**Location**	**Year added to Category 5**	**Previous Impairing Pollutants**	**Previous Pollutant Source**	**Year removed from Category 5**	**Present Category**
Corner Bay	Tenakee Inlet, Baranof Is.	1998	Bark and Woody Debris	LTF	2003/2004	2
Cube Cove	NM Admiralty Is.	1998	Bark and Woody Debris	LTF	2004	2
Hamilton Bay	Kake	1996	Bark and Woody Debris	LTF	2002/2003	2
Hobart Bay	Stephen's Passage	1998	Bark and Woody Debris	LTF	2008	2
Klawock Inlet	Prince of Wales Is.	2002/2003	Bark and Woody Debris	LTF	2006	2
Point Macartney	Kupreanof Is., Kake	1998	Bark and Woody Debris	LTF	2002/2003	2
Salt Lake Bay	Port Frederick, Chichigof Is.	1998	Bark and Woody Debris	LTF	2002/2003	2
Saint John Baptist Bay	Baranof Is.	2000	Bark and Woody Debris	LTF	2002/2003	2
Thorne Bay	Prince of Wales Is.	1994	Bark and Woody Debris	Historical LTF	2008	2, 4a
Tolstoi Bay	Prince of Wales Is.	1998	Bark and Woody Debris	Log Storage Area	2002/2003	2
Tongass Narrows 1	SE of Thomas Basin	2002/2003	Seafood Residue, Processing Wastes	Seafood Processing Facility	2006	2
Tongass Narrows 2	SE of Thomas Basin	2002/2004	Seafood Residue, Processing Wastes	Seafood Processing Facility	2008	2
Twelvemile Arm	Prince of Wales Is.	2002/2003	Bark and Woody Debris	Log Storage Area	2008	2
West Port Frederick	Chichigof Is.	1998	Bark and Woody Debris	LTF	2002/2003	2
Herring Cove	Sitka	1999	Bark and Woody Debris	Log Storage; former Pulp Mill	2002/2003	4a
Silver Bay	Sitka	1994	Pulp Residue, Logs, Bark and Woody debris, Sediment, Wood Decomposition byproducts	Industrial, former Pulp Mill	2003	4a
Ward Cove	Ketchikan	1990	Pulp Residue, Logs, Bark and Woody Debris, Low Dissolved Oxygen, Wood Decomposition byproducts	Industrial	2007	2, 4a
East Port Frederick	NE Chichagof Is.		Bark and Woody Debris	LTF	2004	4b
Klag Bay	W. Chichagof Is.	1996	Metals	Mining	2009	4a
Skagway Harbor	Skagway	1990	Metals	Industrial		5
Salt Chuck Bay	Kasaan, POW	1997	Metals - copper	Mining		5
Rowan Bay	Kuiu Island	1996	Bark and Woody Debris	LTF	2002/2003	2
Saganaw Bay	Kuiu Island	2001	Bark and Woody Debris	LTF	2002/2003	2
Schulze Cove	Fish Bay, Baranof Is.	1998	Bark and Woody Debris	Log Storage	2008	2

Table 1. Impaired water bodies in Southeast Alaska (ADEC 2010a).

Marine contamination may continue long after operations have ceased. One example of a localized habitat affected by prolonged contamination from historic activity is Salt Chuck Bay, adjacent to the community of Kasaan on Prince of Wales Island (Fig. 6). Salt Chuck Bay is a Category 5 water body, listed in 2010 for non-attainment of the toxic and other deleterious organic and inorganic substances standard for metals. The Salt Chuck Mine, an abandoned historic gold, silver, copper and palladium mine that was operational between 1905 and 1941, was listed on the Federal Agency Hazardous Waste Compliance Docket and published in the Federal Register on June 27, 1997, because studies indicated physical and chemical hazards to the public and environment. On September 23, 2009, the Salt Chuck Mine was proposed for addition to the EPA National Priorities List. Copper concentrations found in the intertidal water column exceed state water quality standards. In addition sediment/tailings found in the intertidal zone exceed state guidelines for sediment quality (ADEC 2009a, 2010a). Kasaan was included as one of 18 ADF&G fishing areas and herring were commercially harvested in the area until 1976 (Blackenbeckler 1976; Blackenbeckler and Larson 1982).

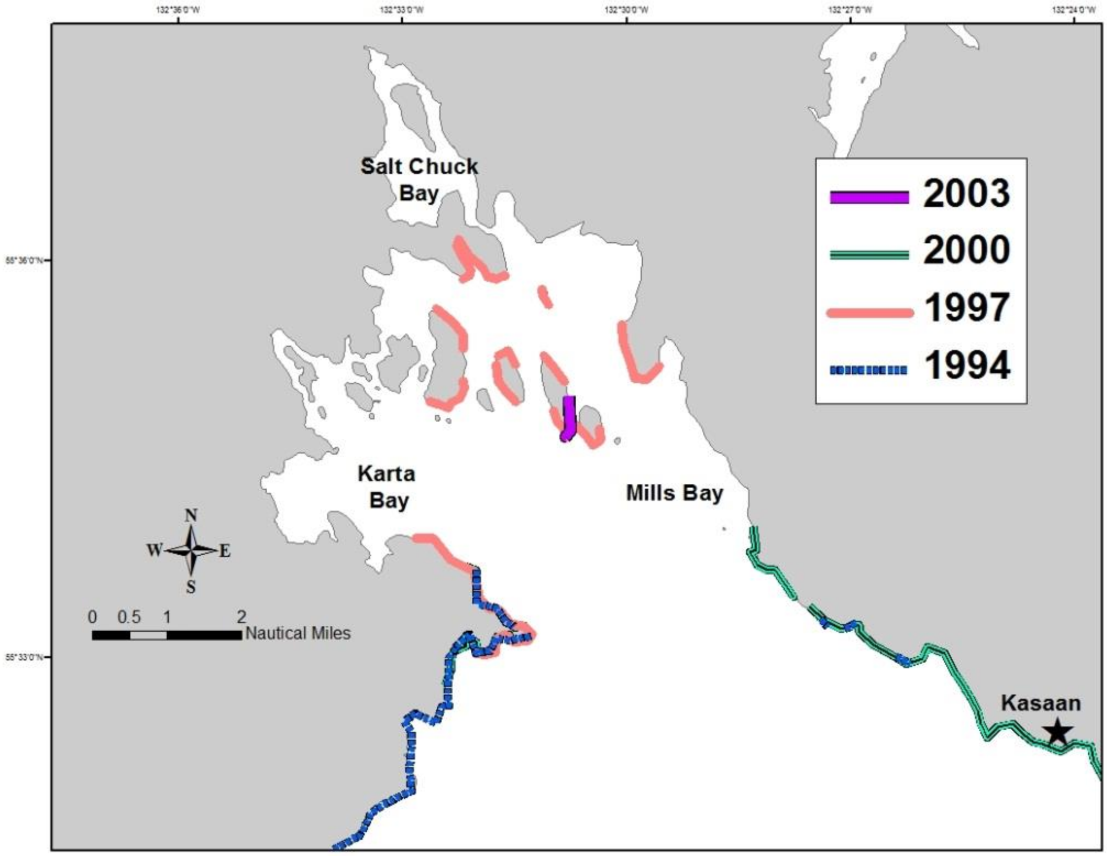


Figure 6. Herring spawn near Salt Chuck Bay, 1994, 1997, 2000 and 2003 (Spawn data courtesy of ADF&G).

6.1.2.4 *Marine Traffic and Noise*

Many herring habitats are not directly adjacent to areas of human habitation. However, impacts may occur indirectly through the presence of vessel traffic and associated effects such as ship waste and noise.

The majority of the visitors in southeast Alaska arrive via cruise ships and visitor numbers have generally been increasing (Fig. 7) (ADCCED 2011). Both large and small vessels move through Southeast Alaska, including cruise ships, the Alaska Marine Highway (AMH) ferries, and commercial and private vessels. Of the vessels that moved through Southeast Alaska (not including deck or construction barges, fishing vessels, passenger vessels on day trips and pleasure craft), the majority of vessel traffic is composed of passenger vessels with overnight accommodations (20%) and cruise ships (19%) even though these vessels are seasonal in nature. The remainder of vessel traffic includes AMH ferries (28%), dry freight barges (19%), freight cargo barges (11%) and log and ore freight ships (3%). In 2012, 28 cruise ships were scheduled to make 450 voyages with the future maximum capacity for cruise ships in Southeast Alaska considered 850 voyages per season (Nuka 2012). Under a general permit, the Alaska Department of Environmental Conservation (ADEC) allows large commercial passenger vessels to discharge black water (toilet water) and gray water (accommodations, galley and laundry water) with certain prohibitions. No foam (except in trace amounts), oily wastes that produce a sheen, floating solids, garbage or grease are allowed. Among other parameters, fecal coliform bacteria, ammonia, copper, nickel and zinc may be discharged, while docked, anchored or underway, with limitations (ADEC 2010b). Large ships may not discharge a contaminant in water bodies that are considered impaired for that contaminant, no wastewater discharge is allowed in Glacier Bay, Tracy Arm is a voluntary no-discharge zone, and no discharge of untreated black water is allowed in the Alexander Archipelago or within 3 miles of the outer coast (Fig. 8). In 2008, discharge limits were exceeded 48 times, with the greatest number for ammonia and copper (ADEC 2009b). A single cruise ship may discharge up to 330,000 gallons/day. In comparison, the city of Petersburg averaged 475, 000 gal/day in April of 2008 (ADEC 2010c). Small cruise ships and AMH ferries are allowed to discharge anywhere (Fig. 8, 9); however all registered small vessels operate under an approved wastewater management plan which include requirements to minimize wastewater discharges while stationary and avoid discharges close to shore and in herring spawning areas (R. Edwardson, personal communication,11/2/2010).

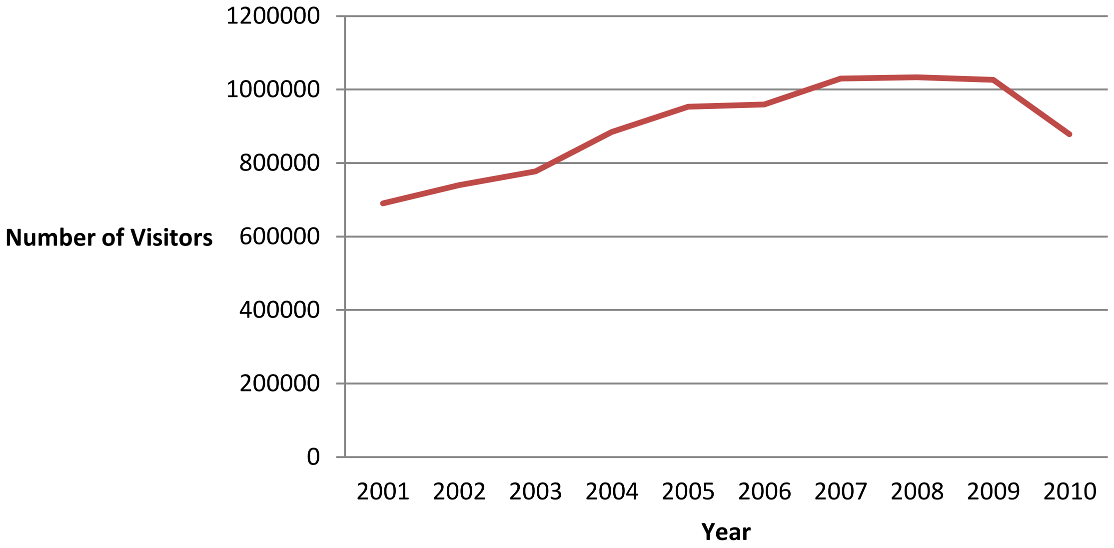
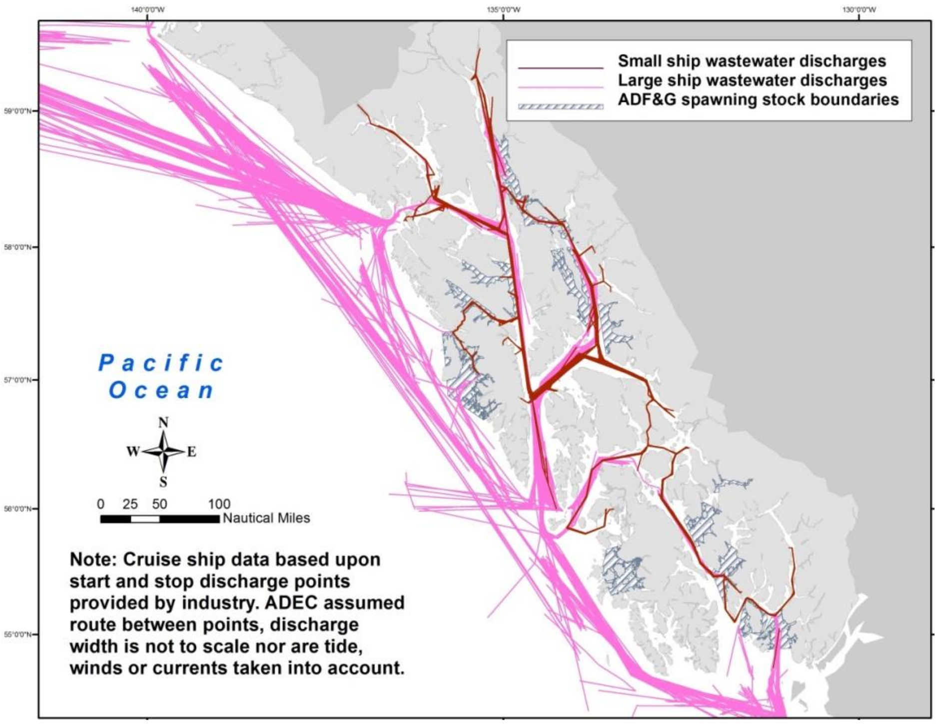


Figure 7. Alaska cruise passenger volume in Southeast Alaska (ADCCED 2011).



Note: Cruise ship data based upon start and stop discharge points provided by industry. ADEC assumed route between points, discharge width is not to scale nor are tide, winds or currents taken into account.

Figure 8. Large and small ship wastewater discharges, June 1 - Sept. 30, 2001 (Data courtesy of ADEC).

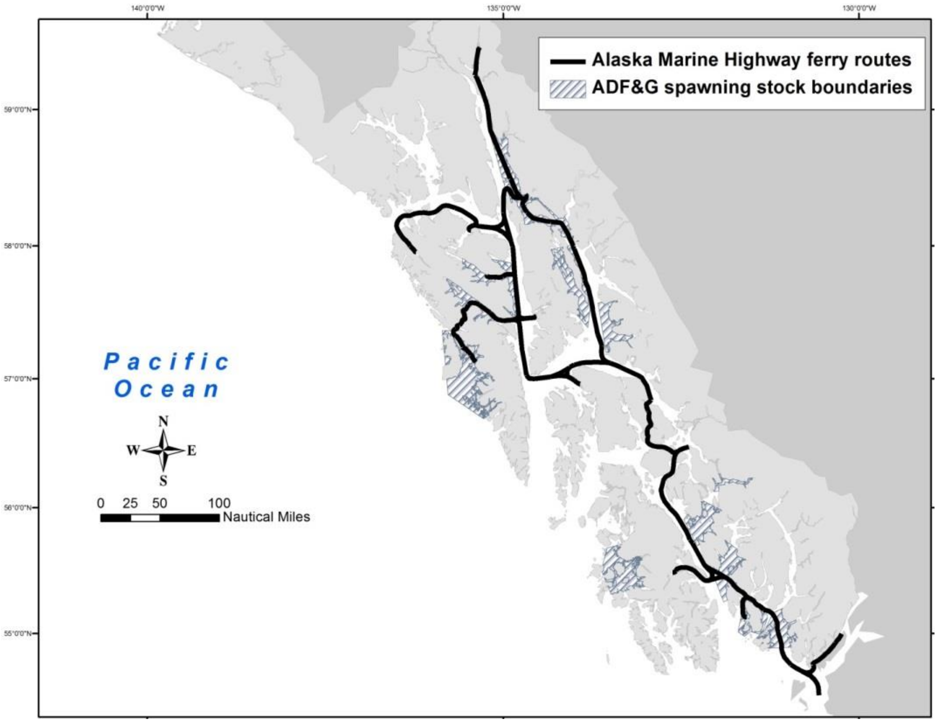


Figure 9. Alaska Marine Highway Ferry routes in southeast Alaska (Data courtesy of ADEC).

Marine noise may also impact fish species, with exposure potentially resulting in the alteration of movement, decreased foraging and reproductive success as well as changes in response to predators (Popper 2003). Many commercial fish species, including herring, have acute directional hearing with the critical frequency band of acute sensitivity in herring measured from about 20 Hz to 1.2 kHz, one of the broadest ranges of all commercial species (Mitson 1995). When subjected to a variety of sounds of natural origin, such as rain, gull cries or killer whale vocalizations, herring did not visibly respond. However, herring did show avoidance behavior when exposed to the sound of large vessels approaching at constant speed and small vessels when accelerating upon approach (Schwarz and Greer 1984). The overall signature of a vessel is comprised of noise from many machinery sources, including engines, pumps, gear boxes, pipework and propellers. Propellers are a major sources of both high and low frequency noise (Mitson and Knudsen 2003). Herring may react in different ways when responding to noise. When herring were exposed to high frequency sound similar to cetacean predators, for example, individual fish stopped feeding, dropped in the water column and started schooling (Wilson and Dill 2002). Schooling fish may increase their swimming speed or depth in response to noise (Pitcher et al. 1996; Wilson and Dill 2002; Kastelein et al. 2007) or exhibit a change in schooling structure (Freon et al. 1992). Herring have also exhibited herding behavior in moving towards and congregating in front of a moving vessel at a certain distance. In the North Sea, herring reacted with a herding response when the distance varied from 25 to 1000 m from the vessel (Misund et al. 1996). It has also been postulated that fishing boats targeting spawning herring may similarly change behavior and disrupt the spawning process.

Auke Bay - A Case Study

"*That herring pot was on the west side of Indian Point, inside Indian Cove—inside Indian Island….There were so many herring that with a garden rake you could rake them on the beach*"
John Bavard (from Mobley 1996)

One location where permanent habitat modification occurred over many years correlated with subsequent changes to herring spawn in the area is Auke Bay, near Juneau. Relatively few residents of Juneau may remember that herring stocks in the Auke Bay area were once rich enough to prompt the building of a nearby cannery in 1916 (Mobley 1996). In the early 1930s, Rounsefell and Dahlgren (1935) included Auke Bay along with Ketchikan, Craig, Frederick Sound and Sitka in describing the main spawning areas in Southeast Alaska. From 1953 to 1981 Lynn Canal herring spawned from Auke Bay to Point Sherman (ADF&G 2007) and during the winters of 1971-1979, biomass estimates consistently exceeded 2502 tons, sufficient to define Auke Bay as a major stock. Between 1943 and 1967, 200-300 tons on average were harvested annually from herring pounds in Indian Cove, Auke Bay and Tee Harbor. From 1968 to 1971, in response to a lucrative Japanese sac roe market, annual harvests increased to an average of 500 tons. (Davidson et al. 2011). In 1983, however, the ADF&G threshold for the area from Auke Bay to Berners Bay (not including Gastineau Channel) was changed from 8 to 10 million pounds (4000 to 5000 tons) due to the rapid decline of the Juneau herring spawn population. Since 1981, very limited spawning has occurred in Auke Bay and the commercial harvest in Lynn Canal, including Auke Bay, has been closed since the 1981-82 season (ADF&G 2007) (Figs. 10 - 13).

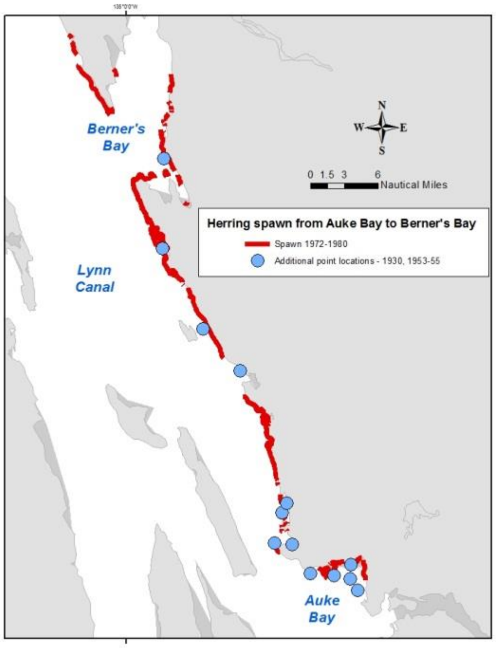


Figure 10. Herring spawn from Auke Bay to Berner’s Bay, 1980 and earlier (Data courtesy of ADF&G).

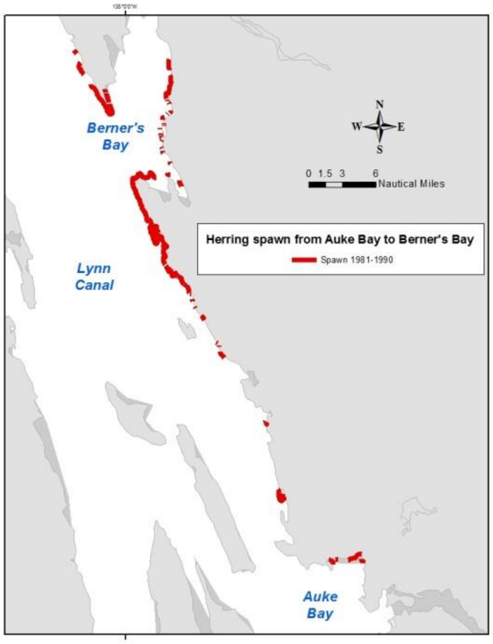


Figure 11. Herring spawn from Auke Bay to Berner's Bay, 1981-1990 (Data courtesy of ADF&G).

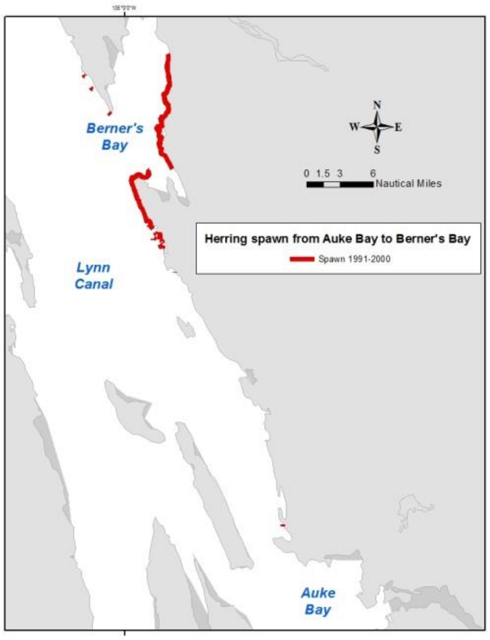


Figure 12. Herring spawn from Auke Bay to Berner's Bay, 1991 - 2000 (Data courtesy of ADF&G).

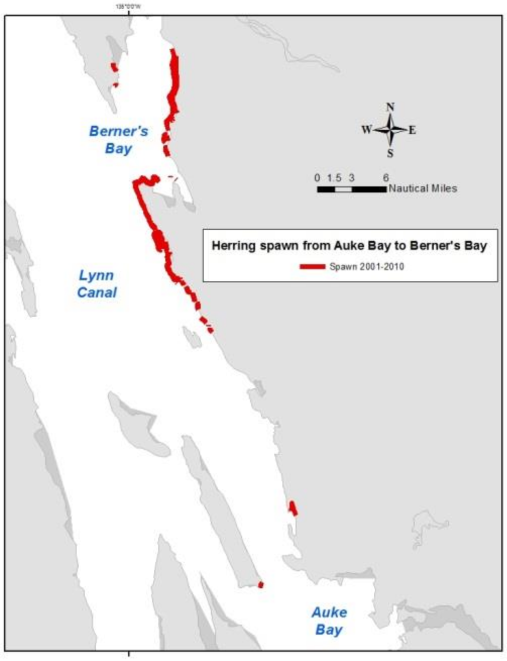


Figure 13. Herring spawn from Auke Bay to Berner's Bay, 2001 - 2010 (Data courtesy of ADF&G).

It is likely that a number of factors contributed to the decline and continued low abundance of herring in Auke Bay. While overfishing over a number of years may have been instrumental in the stock collapse, another potentially significant contributing factor to the decline of herring in Auke Bay is habitat degradation or disturbance (Pritchett et al. 2005). Lynn Canal, including Auke Bay, has experienced a steady increase in shoreline development since the 1900's. Some of the development activities have included public/private/commercial docks, hatcheries, salteries, canneries, residential housing, seafood processing plants, and wastewater treatment facilities, each potentially adding to an overall degradation in habitat. In Auke Nu Cove, for example, the density and biomass of eelgrass as well as the percent cover all declined significantly between 2004 and 2010, coincident with two large intertidal fills of shoreline development projects (P. Harris, personal communication, 6/10/2011), As Pacific herring are one of the most abundant commercially important forage fish species found in eelgrass meadows (Johnson and Thedinga 2005), the loss of eelgrass in Auke Nu Cove may affect the presence of herring in the area. The Proposed Action Alternative of the Statter Harbor Improvements Project includes the further removal of approximately 4 acres of intertidal habitat, including 0.1 acres of eelgrass (HDR 2010).

Cumulative effects of these activities have transformed Auke Bay from a relatively pristine environment into a more urbanized setting. Increased boat traffic, noise, lights, shoreline structures, and reduced water quality in Auke Bay may partially explain why Lynn Canal herring now spawn almost exclusively in other areas and away from an urbanized environment. With fishing no longer an issue, other stressors, including habitat modification, may be preventing the population from increasing to former abundances. The challenge lies in clearly discerning causative factors for decline. Conversely, herring abundance in Sitka Sound, which has also experienced growth in shoreline/marine activity and associated infrastructure, has shown an increasing trend for several decades.

6.1.3 Summary

In Southeast Alaska, there is does not appear to be a single acute threat to herring habitat. Instead, herring are chronically at risk of localized population declines due to modifications in the immediate environment, including changes associated with increasing anthropogenic activity such as shoreline development, pollution, or marine traffic and noise. While no large projects are currently posing a substantial threat to herring habitat, it is clear that anthropogenic activities in general may have cumulative and long lasting impacts on the marine environment, regardless of size or immediate human presence. These activities have increased with human population growth and may have contributed to shifts in regional stocks of herring. At present, both the resident and seasonal non-resident human population of Southeast Alaska is increasing, with the latter primarily through gains in the cruise ship industry. These vessels are authorized to discharge various amounts of waste water including components such as fecal coliform bacteria, ammonia, copper, nickel and zinc, depending upon the ship size and location, but specific effects on herring are unknown. Another method by which herring habitat may be modified is through the introduction of invasive species, such as the colonial tunicate in waters around Sitka which has the potential to smother herring spawning habitat.

Defining the consequences of habitat modification for herring populations is challenging because sufficient information is not available to understand the reliance of herring on particular habitats or the cumulative effects of habitat loss and degradation. It is probable that a synergy of both identified and unidentified factors link herring biology and the surrounding environment, and habitat modification could eventually lead to changes in herring populations. The decline of herring at Auke Bay, for example, was probably a result of multiple stressors, perhaps including permanent changes in the shoreline due to coastal development and consequent changes in water quality and substrate. The challenge lies in clearly discerning causative factors for decline. Identifying causative stressors associated with habitat loss is challenging when other herring spawning locations in southeast Alaska, experiencing similar growth in human population and infrastructure, have shown increases in herring abundance.

6.2 Overutilization

Of all pervasive human disturbances to coastal ecosystems, including water quality degradation and anthropogenic climate change, the primary cause of ecological extinction is overfishing (Jackson et al. 2001). Worldwide, overfishing has been cited as the main cause in 74% of collapsed herring stocks and was considered the sole cause of collapse in 37% of cases (Pearson et al. 1999).

6.2.1 Historic Utilization

Although native people have harvested herring for centuries (Thornton et al. 2010a), large-scale commercial herring fisheries in Southeast Alaska began with salting and pickling operations in the late 1880’s (Larson et al. 2000). With the advent of the longline halibut fishery in 1895, the herring bait fishery also commenced. By the early 1900’s, the demand for salted and pickled herring was replaced by a market for herring industrial products. Herring reduction, which processed fish for oil and meal, began in 1882 with the first reduction plant built at the site of an old whaling station in Killisnoo on Chatham Strait (Reid 1972). By 1927, there were 18 reduction plants in operation (Rounsefell 1930), and the fishery peaked in the 1929–30 season with a harvest of 78,749 short tons (157 million pounds; Larson et al. 2000). By 1938, a sharp harvest decline resulted in only five reduction plants continuing to operate. Herring depletion resulted in the 1939 adoption of regulations prohibiting all commercial fishing, except for bait, in the Cape Ommaney region (the Cape Ommaney area contributed 80% of the total catch between 1927 and 1938). Restrictions to the herring reduction fishery during 1940–1941 failed to stop the stock decline, and in 1942 the entire district was closed to allow for stock rebuilding (Huizer 1952). After reopening in 1943, herring reduction continued on a limited basis until being closed in 1966, in part due to a decline in abundance (Larson et al. 2000).

Throughout this harvest history, technological changes altered fishing efficiency. In the early 1900s, methods being used to find and capture fish were relatively inefficient. However, by the middle of the century, technology was improving rapidly. Power boats with greater net tonnage were first used for seining in the early 1900’s but had replaced row boats in the fishery (Rounsefell 1930). Echo sounders were introduced during the 1940s to help locate the schools of fish, and the use of power blocks in the purse seine fishery became common during the 1950s. Sonar, drum seining, and arc lights were introduced during the 1960s, and the use of larger, faster fishing boats reduced time lost to foul weather and transit to and from the fishing grounds (Hourston 1978). Aerial fish spotting was also introduced in the 1960s (Rogers 1965).

Despite the increase in fishing efficiency and effort, little was known about either the biomass or fishing mortality of herring in Southeast Alaska throughout much of the first half of the century.

By 1925 the growing size of the fishery led to increased concerns over potential overexploitation. This concern resulted in more extensive data collection during 1925–1966 by the U.S. Bureau of Fisheries. Catch quotas, first introduced in 1940, restricted the herring fleet by limiting the total biomass of fish that could be removed annually from specific areas. By 1952, however, the quota system was being questioned. Quotas were historically based upon political and economic considerations, which included both herring biology and interactions with the salmon fishery. Annual landings sometimes exceeded the sum of the district quota because the herring fleet fished outside of an established quota area; in fact, quotas were frequently assigned to areas where the fleet seldom fished. Quotas were eventually discontinued in Kodiak and Prince William Sound, but continued in Southeast Alaska (Fig. 14) (Reid 1971).

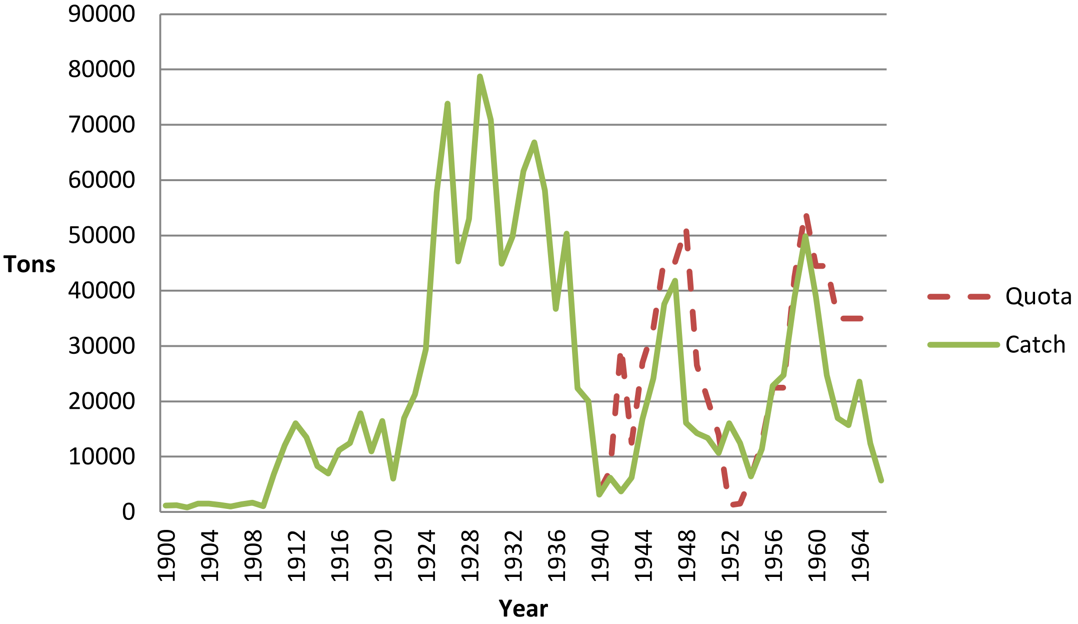


Figure 14. Annual quotas and catches for the commercial herring fisheries of Southeast Alaska, 1900 -1966 (Reid 1971; Pritchett and Hebert 2008).

Although the reduction fishery was closed in 1966, other fisheries also operated prior to this time. In 1959, the commercial cutting and taking of *Macrocystis* kelp fronds laden with herring spawn was initiated from Fish Egg Island near Craig. In 1960, the state legislature prohibited commercial harvesting of spawn on kelp, which was amended in 1961 to allow spawn on kelp to be harvested with a permit. A 50 ton quota was also imposed by the Alaska Board of Fish and Game as well as a prohibition of cutting the kelp fronds. The 1960 and 1961 fisheries were consequently curtailed, but in the fall of 1961 the board rescinded the quota and kelp cutting prohibition and the fishery continued with additional processors which then spread to other areas in southeast Alaska. The spawn-on-kelp (SOK) fishery expanded from two processors and no regulations in 1959 to ten processors and a 150 ton quota by 1965 (Rosier et al. 1964, 1965). By 1966, the SOK fishery included Craig, the McFarland Islands near Hydaburg, and Sitka with a total of 44 processors, 899 skiffs, and 171 large vessels working the fisheries. Although a permit system was initiated in Craig and Hydaburg, a rapid increase in pickers from both Southeast Alaska and areas outside of Alaska continued. In 1967, with fishing time based upon the number of registered “pickers,” the fishery opened for 45 minutes at Sitka and 20 minutes at Craig, with

Hydaburg closed due to reduced spawn deposition. All harvesting was on *Macrocystis* kelp and, although a limited program was undertaken to assess the possible effects of the fishery on kelp beds, the program was discontinued in 1965. In 1968 the herring spawn on *Macrocystis* kelp fishery was not opened in any areas due to insufficient deposition in Hydaburg and the lack of commercial quality kelp in Craig or Sitka, although other forms of kelp were harvested. Spawning activities in Craig and Hydaburg were also erratic with considerable shifting of spawning location (Rosier et al. 1967a, 1967b, 1968). The wild SOK fishery was completely phased out by 1969 (Pritchett and Hebert 2008).

In the 1970s, both the sac roe (SR) fishery, which removes herring immediately prior to spawning when egg maturity is highest, and the winter bait and food (WBF) fishery were operational. In the 1976-77 season, 8500 tons were landed in the SR and WBF fisheries in Southeast Alaska, with 2550 tons landed in the SR fishery and 6300 tons landed in in the WBF. Hydroacoustics were the main method of biomass assessment with a 25% egg mortality/predation correction factor added to the estimate (Blankenbeckler 1978a, 1978b). Between 1977 and 1980, the SR and WBF catch averaged 7250 tons. The predominant fishery type also shifted during this time with the WBF harvest declining from about 4000 to 2500 tons and the SR harvest increasing from about 2000 to 6500 tons (Fig. 15). Biomass estimates with a target harvest rate of 10 – 20% continued on the major stocks, although the actual harvest was sometimes higher, e.g., harvest rates in several areas exceeded 25% of the estimated spawning biomass in 1976-77(Blankenbeckler 1978). Managers also limited harvests on unsurveyed stocks to 100 tons, with a 1000 ton estimate required for wintering areas before fishing was allowed, and Pybus, Gambier and Helm Bays were closed to SR fishery because the available biomass was too small to consider a controllable fishery (Blankenbeckler and Larson 1982). By 1980, the quota and catch for the SR fishery had also surpassed the WBF quota and catch (Fig. 16).

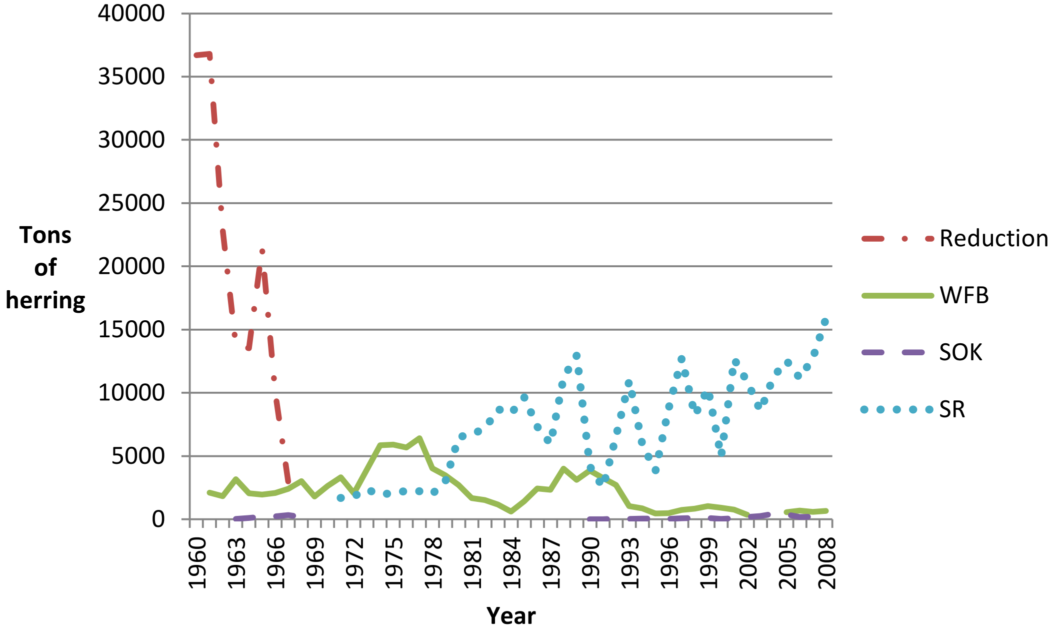


Figure 15. Southeast annual herring catch in the reduction, winter bait and food (WBF), spawn-on-kelp (SOK) and sac roe (SR) fisheries (Pritchett and Hebert 2008).

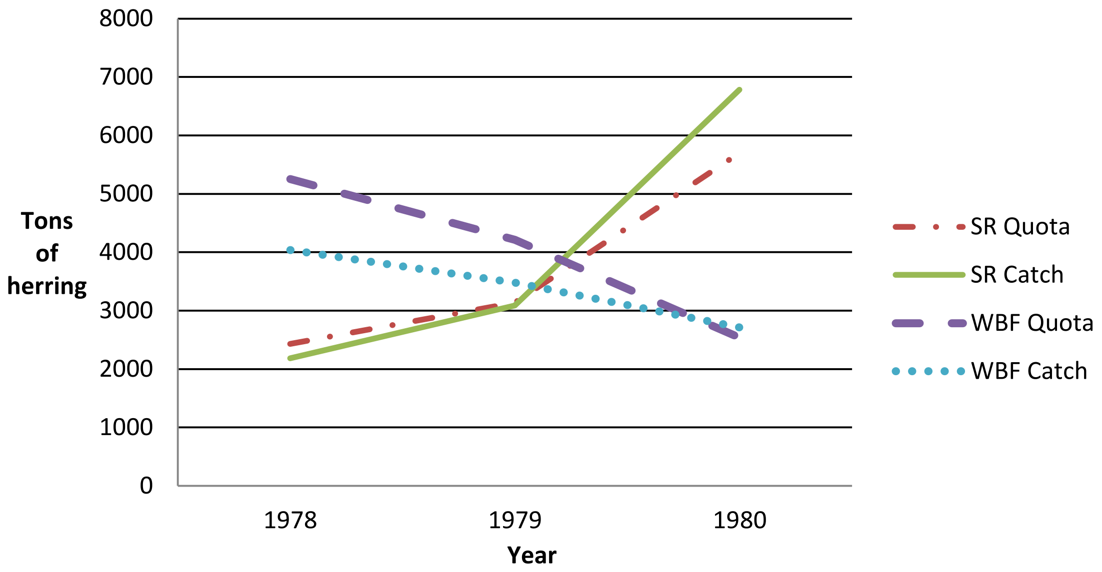


Figure 16. Quotas and catches in the sac roe and winter bait and food herring fisheries in Southeast Alaska, 1978-1980 (Blankenbeckler and Larson 1982a).

6.2.2 Current Utilization

Relative to the biomass removed through commercial fishing, utilization of herring in Southeast Alaska for scientific, recreational and personal use is very small (Fig. 17). Although only a minor portion of the total catch is removed through subsistence and personal use, herring plays a vital role in the lifestyle and culture of personal and subsistence users and also in Southeast Alaskan ecosystems. Consequently, controversy has arisen over the commercial harvest as possibly having too great an impact on availability for noncommercial users, as well as for marine and bird species that prey upon herring. Despite the controversy, the commercial fishery has become a significant industry with exvessel values ranging from $1,971,960 in 1991 to $17,342,622 in 1996 (Pritchett and Hebert 2008).

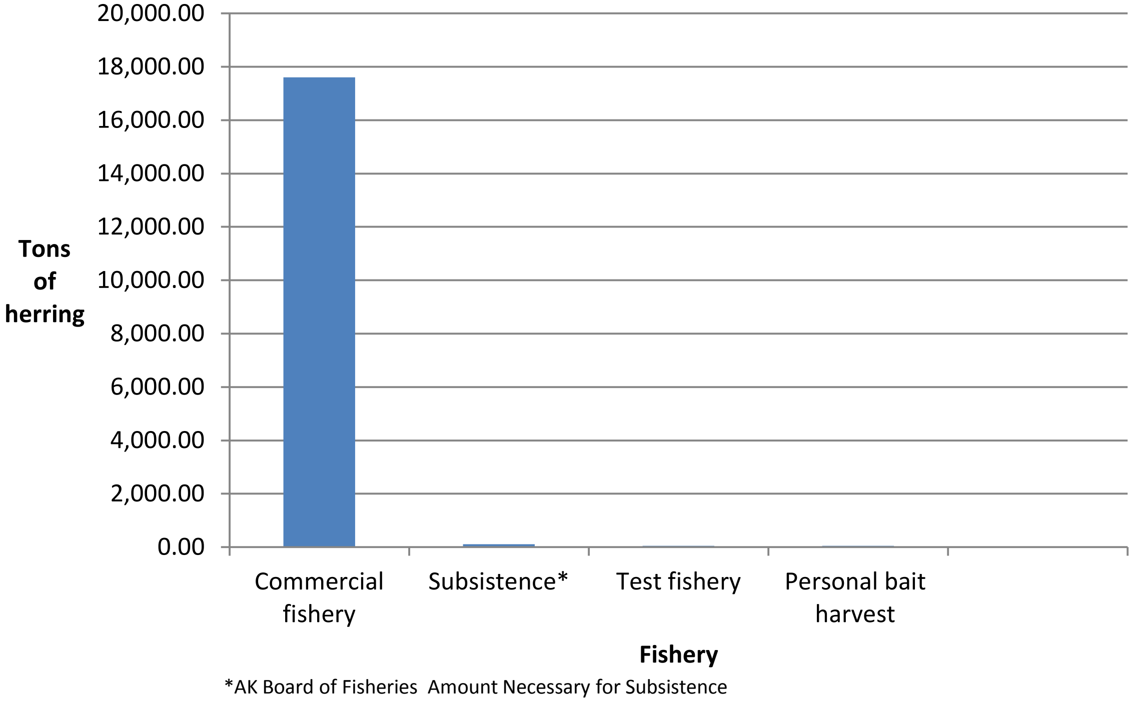


Figure 17. Relative harvest amounts for Sitka herring fisheries in 2010 (Davidson et al. 2011).

Since 1980, ADF&G has conducted stock assessments in at least nine major spawning areas in Southeast Alaska, including Sitka Sound, Seymour Canal, Craig/Klawock, Hobart Bay/Port Houghton, West Behm Canal, Tenakee Inlet, Hoonah Sound, Ernest Sound and Revilla Channel. Within these spawning regions, ADF&G manages three limited entry commercial herring fisheries, including SR, SOK pound, and WBF. The majority of herring is harvested in the SR fishery. The 2010 herring catch, for example, was approximately composed of 93% from the SR fishery, 2% from the SOK fishery, 4% from WBF and <1% from test fisheries or personal use bait (Fig.18) (Davidson et al. 2011).

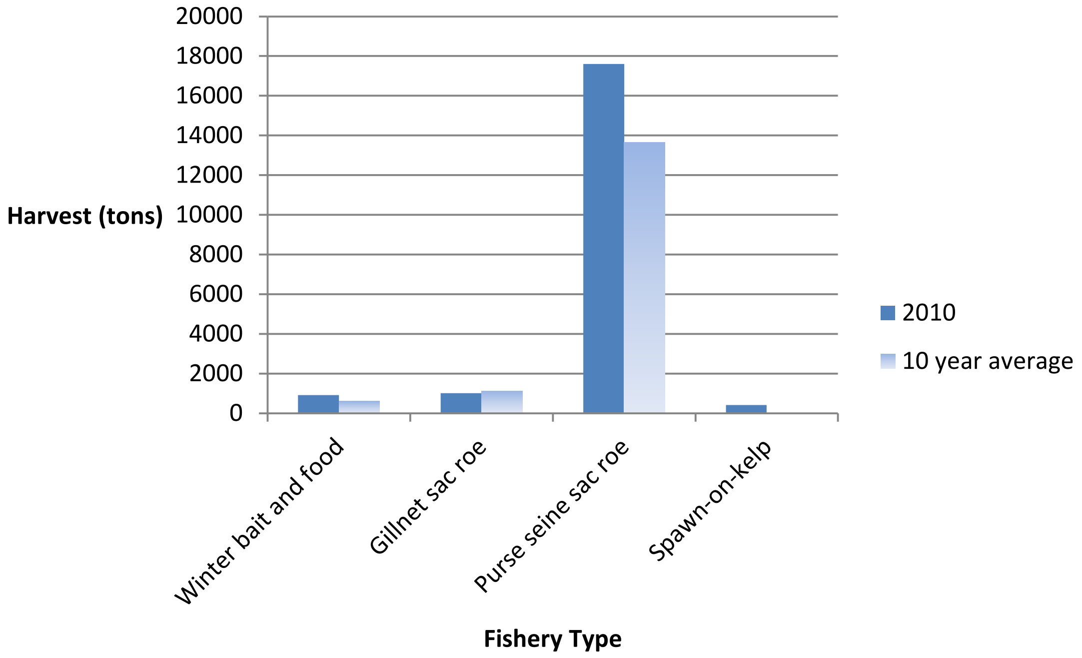


Figure 18. 2010 and 10-year average Pacific herring harvest by commercial fishery type (Davidson et al. 2011).

<u>Sac roe</u>

The SR fishery was developed in the early 1970's and occurs with both purse seine and set gillnet gear immediately before spawning. The SR fishery occurs in six primary fishing areas in Southeast Alaska with purse seine fisheries in Sitka Sound and Lynn Canal, and three gillnet fisheries in Revilla Channel, Seymour Canal and Hobart Bay/Port Houghton. A fishery with gillnet and purse seine gears used in alternate years is open in West Behm Canal when estimated biomass exceeds 6000 tons (Bergmann et al. 2009).

Relative to other commercial fisheries, the SR fishery removes the greatest percentage of herring biomass (Woodby et al. 2005). Within the sac roe fisheries, the Sitka Sound fishery is significantly larger than the others with a spawning biomass threshold of 25,000 tons as compared to the next largest thresholds of 6,000 tons for Revilla Channel and West Behm Canal. In 2010, approximately 18,615 tons of herring were harvested in commercial SR fisheries in Southeast Alaska with 18,033 tons from Sitka Sound (Fig. 19) (Thynes et al. 2011)

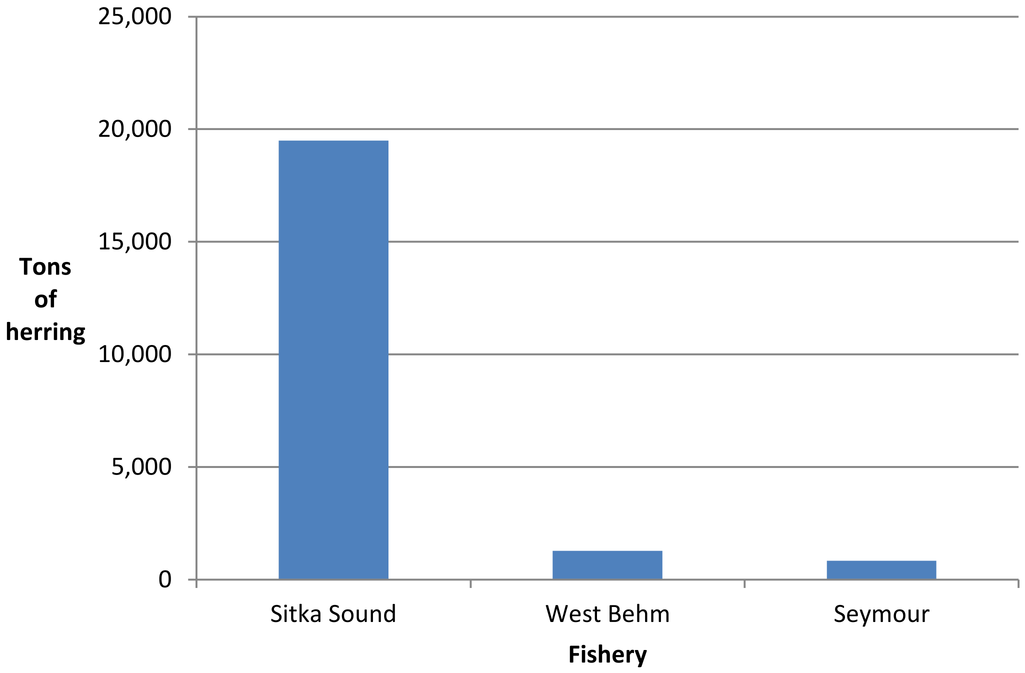


Figure 19. Relative contribution of each fishery to the 2010 herring sac roe harvest in Southeast Alaska (Thynes et al. 2011).

Spawn-on-kelp

The spawn-on-kelp pound fishery is further divided into a closed-pound-fishery and an open-pound-fishery. The former involves seining for mature herring that are then released into a net impoundment containing kelp. The fish spawn on the kelp, are then released, and the kelp with eggs sold. The open-pound fishery involves unconstrained mature herring naturally spawning on kelp suspended on a floating structure, after which the kelp and eggs are sold. The spawn-on-kelp fisheries and the year of inception include Craig-Klawock (1992), Ernest Sound (2003), Hoonah Sound (1990), and Tenakee Inlet (2003) (Breese et al. 2010).

Winter bait and food

Historically, Southeast Alaska herring are used for most of the bait for Alaskan commercial longline and pot vessels (Pritchett and Hebert 2008). Harvest is generally during the fall and winter, when fish in discrete wintering schools are taken by purse seine gear (Pritchett and Hebert 2008). Areas where herring are harvested include Craig/Klawock (1960's), Ernest Sound (1969) and Tenakee Inlet (1978) (Breese et al. 2010).

6.2.3 Indices of Overutilization

Because the volume of herring utilized for scientific, recreational and personal use is small relative to commercial use, the threat of Southeast Alaska herring overutilization translates into the threat of commercial overfishing. Simply defined, overfishing may be considered the harvesting of a fish population at a rate greater than the population can replenish itself through growth and reproduction (Rosenberg 2003). However, a variety of parameters and methods may be used to explicitly describe overfishing in a population. In the U.S., for example, at least 117 definitions of overfishing have been used among fisheries. Some definitions are based on fishing mortality rate, some on stock abundance and some on both (Rosenberg 1993; Rosenberg and

Restrepo 1994). The ADF&G has established biomass thresholds for herring fishing in Southeast Alaska, but has not explicitly defined overfishing (K. Hebert, personal communication, 12/8/10).

Indices which have been used to determine the intensity of fishing may relate to fishery reference points, such as harvest rates, guideline harvest levels and established threshold levels; or life history characteristics and population trends such as abundance, size-based indicators; and appearance and disappearance of populations. No single index fully describes trends in herring stocks relative to fishing impacts, so assessment of an overfishing status must be interpreted across multiple indices.

6.2.3.1 Fishery reference points

Fishing mortality and natural mortality

A rule in fisheries management that appears to serve as an indicator for risk of collapse pertains to the ratio of fishing mortality, F, to natural mortality, M. Research on forage fish collapse indicates that sustainability may be associated with fishing mortality rates that are substantially lower than natural mortality rates, or $F/M \leq 0.67$ (Patterson 1992; Pikitch et al. 2012). In assessing data from three Southeast Alaska herring stocks, using M modeled by ADF&G, it is apparent that this rule is generally followed, with occasional exceptions. In Sitka Sound between 1980 and 2011, $F/M > 0.67$ in 3 out of 32 years (1999, 2001 and 2002) or 9.4% of the time. In Seymour Canal between 1980 and 2010 $F/M > 0.67$ in 2 out of 31 years (1999 and 2002) or 6.5% of the time. The 2011 F/M in Seymour Canal was not available due to harvest data considered confidential (Thynes et al. 2013). In Craig between 1980 and 2011, F/M did not exceed 0.67.

Abundance relative to threshold

One definition of overfishing involves harvest levels that may drive stock abundance below prescribed levels. Optimally, the threshold is the minimum level of mature herring biomass needed to provide for sustained yield and maintain biological productivity over the long-term (Hebert 2011). A stock may be considered overfished when exploitation rates have driven the stock below a prescribed biomass threshold (Quinn et al. 1990; Rosenberg 2009; NMFS 2009).

Since 1980, the number of stocks, including Lynn Canal and Kah Shakes, that remain above threshold levels has remained fairly consistent. However, Kah Shakes is not included as one of the nine stocks consistently surveyed. Significant spawn has not been observed since 2001, but surveys are not conducted around Annette Island, so the area trend is unclear (Hebert 2009). If Kah Shakes is excluded, the number of stocks with biomass above threshold levels shows an increasing trend (Fig. 20).

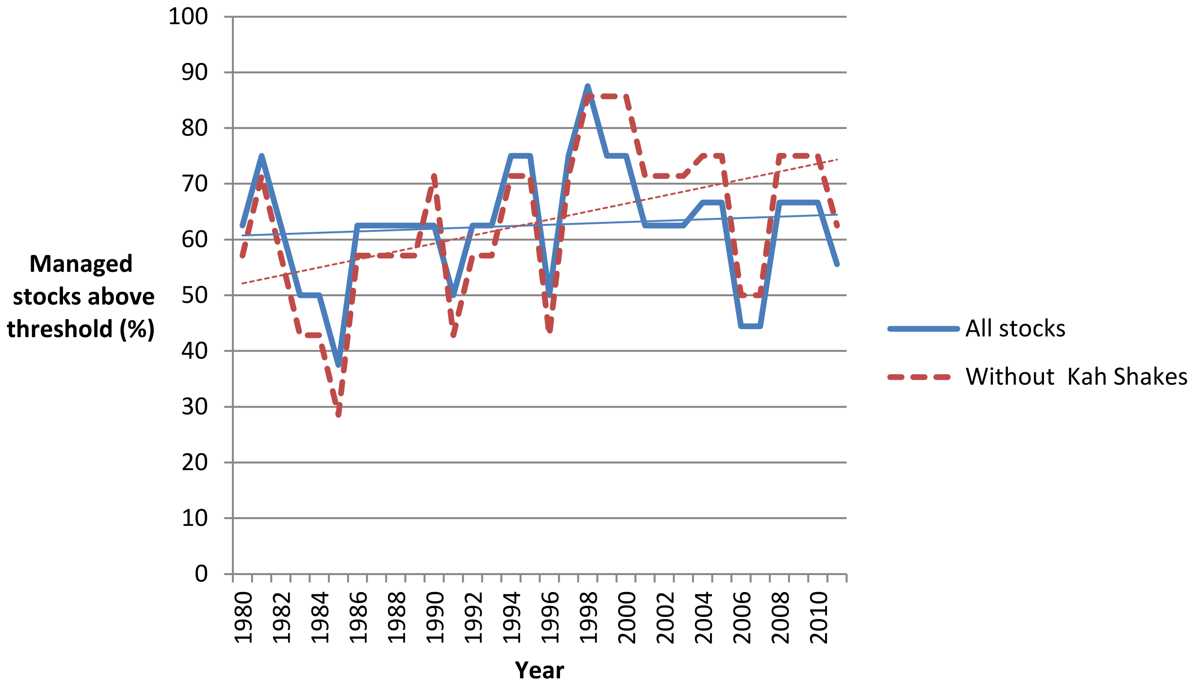


Figure 20. Percent of managed stocks with biomass above threshold (Breese et al. 2012; Thynes et al. 2012).

Level of exploitation, guideline harvest limit and exploitation rate

Another definition of overfishing involves fishing pressure and compliance. While it is not uncommon for the GHL to be exceeded, the average harvest has generally been very close to the GHL (Table 2). Furthermore, overages of the GHL do not necessarily indicate fishing beyond management limits, i.e. a greater than a 20% exploitation rate. In Sitka Sound, for example, while the 1982 harvest was 145% of the GHL, the exploitation rate was 13%, significantly below the 20% limit. Exceeding the GHL may also be a deliberate management measure. The 1992 harvest in Sitka Sound exceeded the GHL by 160%, but this was due to an additional allowance when the return was substantially greater than expected (ADF&G 2013).

Stock	Years	Percent of time GHL exceeded	Average harvest relative to GHL (%)
Sitka Sound	1980-2011	59	105
Other stocks	1980-2010*	44	98

*As data is available per stock

Table 2. Actual vs. Guideline Harvest Levels (Bergman et al. 2009; Thynes 2010; data courtesy of ADF&G).

Another index of fishing pressure is the exploitation rate. When 1980 – 2010 estimates for all stocks excluding Sitka are compiled, the exploitation rates are substantially lower than 20% (Fig. 21). Whether the harvest rate exceeds the management limit of 20% appears to depend primarily on how the hindcast estimate compares to the forecast estimate. Over the last 30 years, hindcast estimates have most often been larger than the forecast estimates. Consequently, the final exploitation rate is generally lower and more conservative than the target rate set pre-season. In Sitka Sound, for example, the harvest exploitation rate is, on average, 82% of the target harvest rate. However, occasionally the hindcast estimates are less than than the forecast estimates which may result in an exploitation rate greater than 20%. In Sitka Sound between 1980 and 2011, the hindcast estimates have been less than the forecast estimates in only 5 of 32 years. As a result, however, in each of these years the exploitation rate exceeded 20% (range 21 – 28%). Under most circumstances, observations on the fishing grounds allow managers to adaptively modify the harvest appropriate to the return, either through increasing or decreasing the harvest. However, it is also possible that, although rare, the 20% exploitation rate is exceeded prior to this “ground truthing” that occurs during spawning events. For example, during the 1999/2000 season, the entire GHL of Port Houghton/ Hobart Bay was harvested in the winter bait fishery. The forecast was 3600 tons with a GHL of 418 tons. The WBF catch was 432 tons (ADF&G 2000a). With the commencement of spawning, the hindcast estimate was 1293 tons (ADF&G 2012), substantially lower than the forecast, and as a result the catch was about 36% of the biomass.

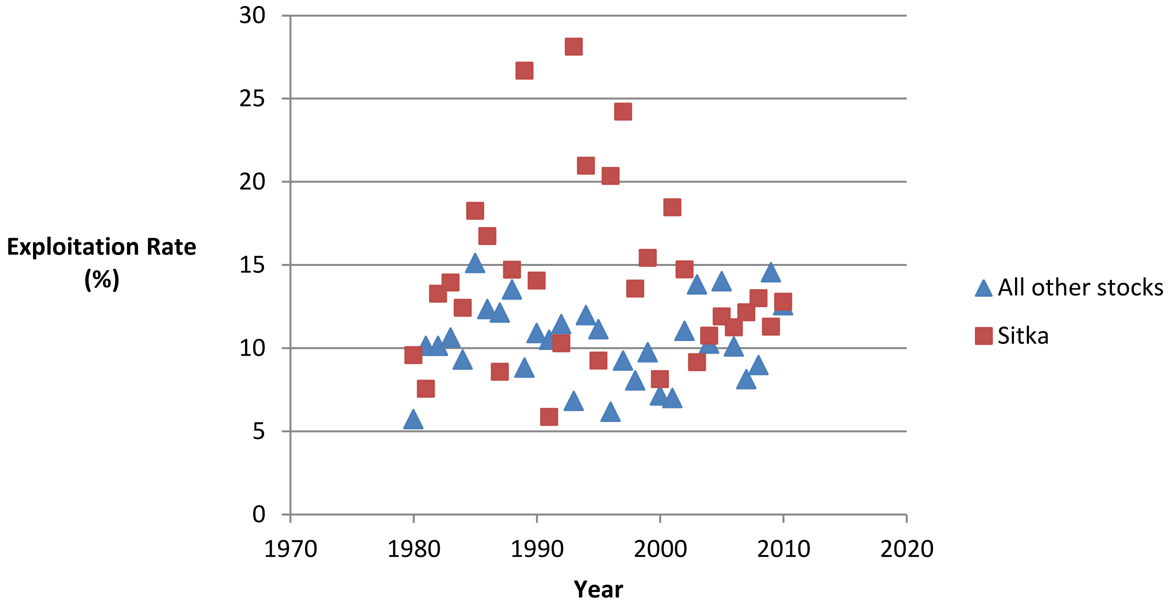


Figure 21. Exploitation rate of combined stocks and Sitka, 1980 – 2010 (Data courtesy of ADF&G).

6.2.3.2 *Biological reference points*

<u>Trends in abundance</u>

A low population density is significantly associated with a high extinction risk (Purvis et al. 2000) and abundance is one of the four parmeters in evaluating population status (McElhany et al. 2000). Because the threat of overexploitation is primarily associated with a decreased abundance or population decline (Hutchings and Reynolds 2004), an evaluation of abundance is paramount in extinction risk assessment. The combined biomass of the nine ADF&G managed stocks, including Seymour Canal, Hoonah Sound, Craig, Ernest Sound, West Behm Canal, Hobart/Houghton, Tenakee and Kah Shakes with and without Sitka Sound is illustrated in Figure 22. A positive trend is apparent, although the magnitude of increase differs substantially when Sitka is excluded. Trends in abundance for individual stocks are included in Appendix A. Figs A1- A9.

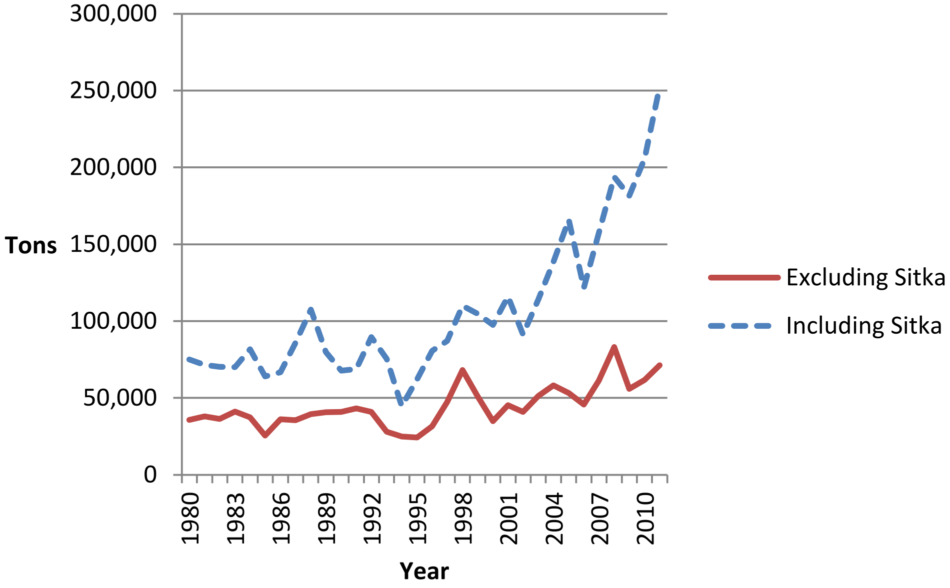


Figure 22. Estimated combined herring biomass of nine ADF&G managed stocks, with and without Sitka (Data courtesy of ADF&G).

Recruitment

In a closed population, an increase in abundance is controlled by the level of recruitment, or the addition of new generations of young fish (NMFS 2009a). In marine fisheries, recruitment is generally considered the first age where fishing occurs (Myers 2008); with Pacific herring, recruitment may be defined as the age when young fish first join the parent spawning stock and are consequently available to the fishery. This typically occurs at about 3 years, although some fish may not recruit until age 6 or 7 (Hay 1985; Zheng 1996; ADF&G 2013).

Because the recruitment rate is one of the most important determinants of the capacity of a stock to sustain exploitation (Getz 1987), predicting recruitment is one of the most important concerns for fisheries managers (Williams 1999). An understanding of recruitment processes is essential in understanding the population dynamics and predicting the responses to exploitation (Rickman et al. 2000). Following the collapse of all major herring stocks in the Northeast Atlantic in the 1960’s and 1970’s, management advice included the importance of effective recruitment studies in order to monitor recruitment failure (Jakobsson 1985).

One of the goals of fisheries management is to keep the spawning stock biomass above the level where recruitment becomes highly sensitive to the size of the spawning stock. Although herring are among fish species with the most variable recruitment, recruitment in herring does relate to the spawning stock size. While recruitment in most Atlantic and Pacific herring is compensatory density-dependent, with survival rates decreasing from eggs to recruits as the spawning biomass and competition for resources increases (Zheng 1996), the highest recruitment in clupeids, including herring from Southeast Alaska, tends to occur when spawner abundance is high (Zheng 1996; Carlile 1998a). Similarly, the lowest recruitment occurs when spawner abundance is low, although the effect is not as pronounced (Myers and Barrowman 1996). When the spawning biomass starts to decrease, increased fitness of a population may theoretically result due to more readily available resources. However, the number of reproducing animals may also be reduced to a level low enough to result in depensation, where reduced reproductive output (the Allee effect), predator saturation and environmental conditions can result in low per capita production of new recruits to a population and increased extinction risk (Frank and Brickman 2000; Sadovy 2001; Dulvy et al. 2003; Hutchings and Reynolds 2004). Evidence for depensation includes decreased survival at low population levels, with predation cited as a primary mechanism (Frank and Brickman 2000; Myers et al. 1995). Due to Allee effects, species that show group mating, defense and schooling as characteristic social behavior may be at increased risk of extinction under heavy exploitation. Under the assumption of Allee effects, when a stock falls below its critical level, self-regeneration is no longer possible and stock rebuilding only occurs through immigration (Frank and Brickman 2000). It is imperative, therefore, that herring stocks are managed to maintain sufficient spawner abundance to yield high recruitment. Recruitment overfishing occurs when this goal is not met; recruitment becomes highly sensitive to the size of the spawning stock (Myers and Barrowman 1996; Freon et al. 2005).

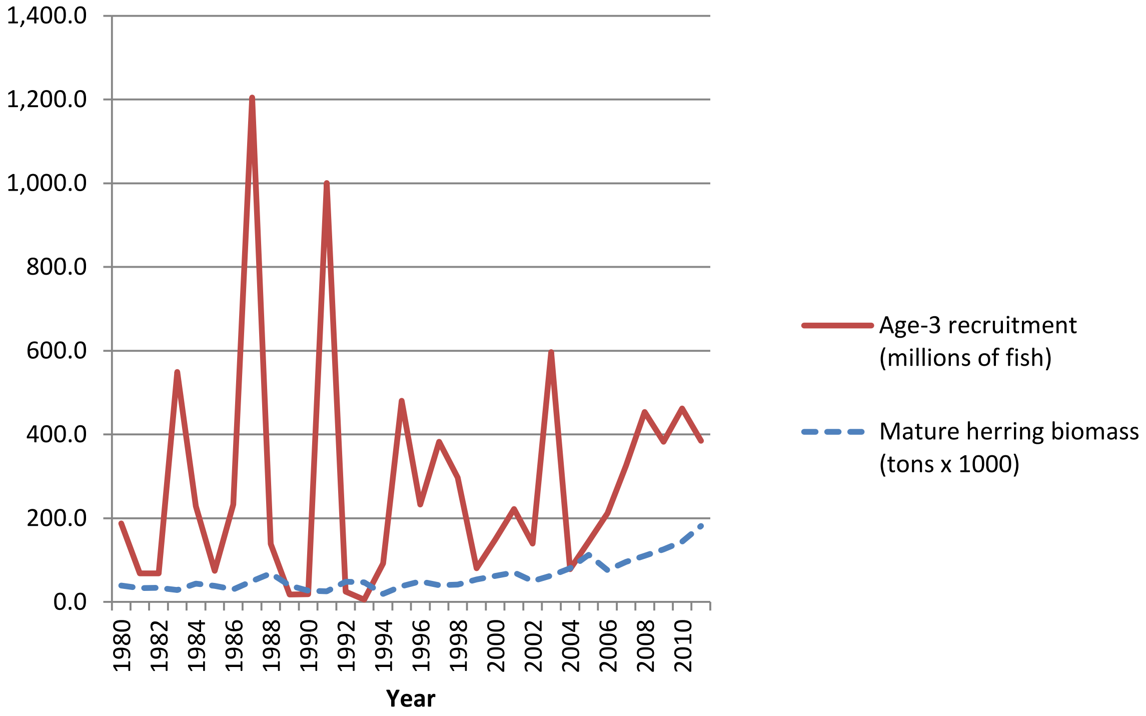


Figure 23. Recruitment of immature and mature age-3 herring (prior to spring fishery) into Sitka Sound population (Data courtesy ADF&G).

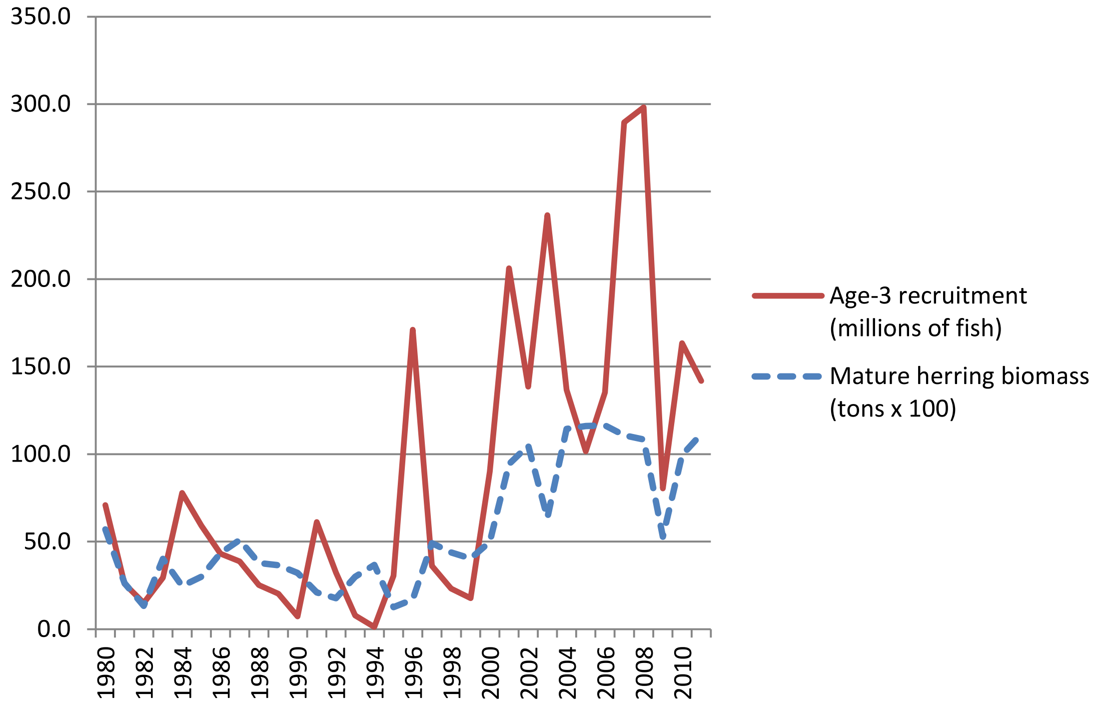


Figure 24. Recruitment of immature and mature age-3 herring (prior to spring fishery) into Seymour Canal population (Data courtesy ADF&G).

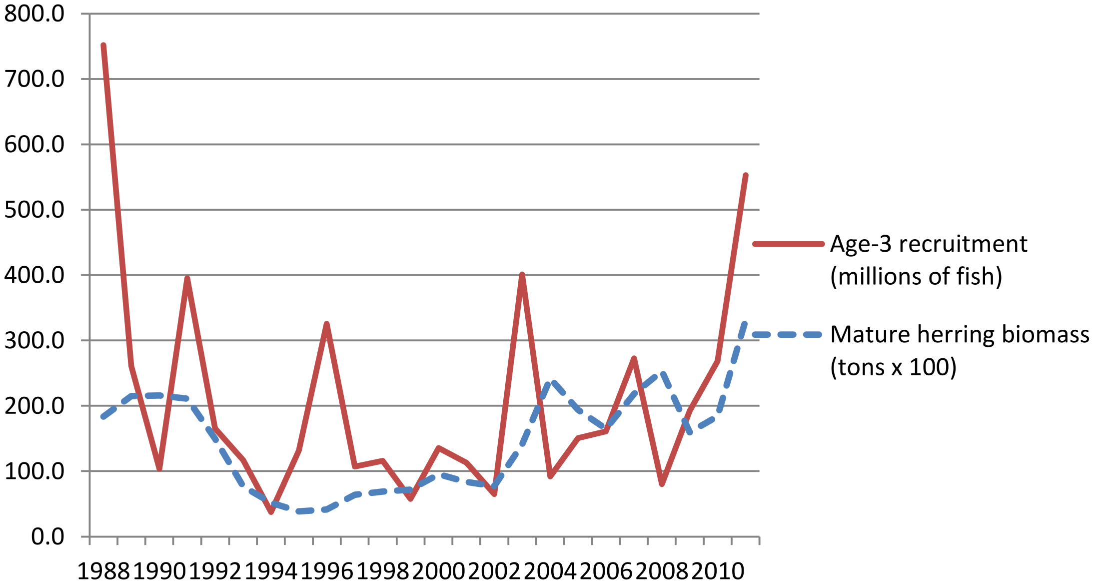


Figure 25. Recruitment of immature and mature age-3 herring (prior to spring fishery) into Craig spawning population (Data courtesy ADF&G).

Size-based indicators (Appendix A., Figs. A10 - A30)
Fishing pressure may manifest on a population level in a variety of ways and result in a multitude of consequences. Along with changes in abundance, fishing pressure may nonrandomly modify size composition and life history, genetics, predator-prey and competition dynamics (Law 2000; Nicholson and Jennings 2004; Jennings and Dulvy 2005; Shin et al. 2005; Shuter and Abrams 2005). While environmental factors affecting growth and maturation fluctuate, selection pressure as a result of fishing may be directional, affecting cohort after cohort (Law 2000).

Forage fish species such as herring may exhibit survival “bet-hedging” strategies, including long-tailed age structures (long tail of old individuals in the age distribution), age-related differences in spawning locations and timing and increased quality and quantity of eggs in older or larger fish. These strategies can increase larval survival rate under harsh and variable conditions, thereby dampening environmental stochasticity and helping to stabilize the population (Hsieh et al. 2006, 2008). Long lived spawners may be essential for an exploited stock to persist because of a “storage effect” whereby a stock will persist as long as there are sufficient adults to outlive periods unfavorable to successful recruitment and spawning (Warner and Chesson 1985; Francis 1997). Age truncation with fishing may undermine this bet-hedging (Hsieh et al. 2010). Long life spans of adults are necessarily associated with low rates or mortality. Fishing generally removes older and larger fish from a population, thereby imposing a selection pressure opposite to that of natural mortality (Berkeley et al. 2004).

The impact of harvesting policies may consequently change over time, with the truncation of age and size structure reducing natural and characteristic longevity and often resulting in localized depletions (Longhurst 2002). Coupled with a truncated age structure, these changes in age and size structure may also lead to increased variability in recruitment and a greater interannual instability in stock size which reduces the capacity of the population to buffer environmental effects and makes effective management more difficult (Rickman et al. 2000; Hsieh et al. 2006; Anderson et al. 2008; Perry 2010). Through the alteration of age and spatial structures, exploited populations may consequently be more prone to catastrophic shifts (Hsieh et al. 2008).

Conversely, life history characteristics may also signal the recovery of a depleted herring stock. Recovery may lead to the redistribution of recently hatched larvae to historical spawning grounds as well broadening of size and age composition (Melvin and Stephenson 2007), although parameters may not necessarily return to pre-depletion levels. For example, with the collapse of Norwegian spring-spawning herring, the world’s largest herring stock, in the late 1960’s, size based indicators did not completely return to pre-collapse levels with renewed stock abundance in the late 1990’s (Englehard and Heino 2002).

Size-based metrics may perhaps be the most fundamental indicator of the impact of fishing on fish communities. The age and size structure of a stock, combined with the spatial distribution of recruitment, may be as important as spawning biomass in long-term sustainability (Berkeley et al. 2004). There are consequently a number of life history indices, such as age and size, that are commonly used to assess the impact of fishing on populations, although no single size-based indicator may serve as an accurate indicator of heavy fishing and parameters require interpretation with caution as changes in the size distribution may have more than one cause

(Schweigert et al. 2002; Shin et al. 2005). While the decadal time scale required to link metrics and fishing effort precludes them as indicators to guide management decisions over a shorter time frames (Nicholson and Jennings 2004), size-based indicators may be used as a management tool. In British Columbia, for example, a decline in size at age trends resulted in their incorporation into the management decision making process since 1999, with an adjustment of the potential harvest based on the proportion of the stock estimated to be available to the gill net sector (since purse seines are considered non-selective) (Schweigert 2004).

Age

In many fish species as well as Pacific herring, older spawning females tend to produce larger eggs and subsequently larger larvae than do younger, smaller adults (Hay 1985; Chambers and Leggett 1996). In British Columbia, fecundity was found to be almost directly proportional to body weight with a larger female producing up to 180% more than a recruit spawner and the maximum reproductive value occurring between the ages of 9 and 10 (Ware 1985). These older fish may play a pivotal role in replenishing stocks, with larvae from older fish surviving starvation longer and growing faster on the same diet which is then reflected in subsequent recruitment (Berkeley et al. 2004). The percentage of dead and abnormal spawners in the progeny of probable first time spawners (4 -5 year old parent fish) has been found to be higher than the offspring of 6 – 9 year old fish (Ojaveer 2006). Populations composed of small and younger individuals will therefore have reduced reproductive potential (Scott et al. 1999) and potentially increased variance in offspring survival (Hutchings and Myers 1993). Furthermore, a stock with a higher proportion of older and larger fish should produce more eggs providing a higher probability of recruitment success (Schweigert et al. 2007). A clupeoid collapse can be due to heavy fishing mortality which reduces the mean age of the population and forces the very young fish to sustain the reproductive load with a decreased age at first reproduction (Ware 1985). If the environment intervenes in some way to cause excessive mortality of the eggs, larvae or small juveniles, successive poor year classes with continued fishing may reduce the population below the critical minimum stock size (Lasker 1985). Furthermore, while age truncation may occur following even moderate levels of exploitation (Berkeley et al. 2004), in datasets from a multitude of high latitude fisheries the decline in larger fish increased with the intensity of over-exploitation (Bianchi et al. 2000). The population decline of Cherry Point herring in Washington, for example, once the largest herring population in the state, corresponded to a collapse of the age structure, with the loss of reproductive potential of older fish leading to a decline possibly due to a synergy of stressors including overexploitation, habitat alteration, disease and climate change. A retrospective assessment of the Cherry Point herring age structure included a general decline in the population, with some wild fluctuation; initial increases in the number of age 2 and 3 fish followed by fluctuations and then low numbers; and a concurrent decrease in age 4 and older fish until they were essentially extinct (Landis et al. 2004; Landis and Bryant 2010). The reduced age structure and increased natural mortality of these fish, with a biomass decline from 13,606 tonnes in 1973 to 733 tonnes in 2000, may have also resulted in increased larval abnormalities including low weights and lengths at hatch and an increased incidence of skeletal malformations (Hershberger 2005).

Pacific herring in Southeast Alaska do not currently appear to be undergoing the truncation as observed for Cherry Point herring. The overall proportion of older fish (age 9+) in the sampled herring population has substantially increased from 0.3% in the years 1929 – 1966 to about 3% during 1987 – 2011 (Reid 1971; ADF&G data).

Heavy exploitation by the reduction fishery prior to the 1920s may have caused a relative scarcity of older and larger fish after 1918 (Huizer 1952). Between the 1920s and early 1940s, the reduction industry continued to significantly deplete herring biomass. During this period, the average age and percent contribution of age-3 to herring sampled declined slightly while the percent contribution of age-9+ showed a marked decline. Between 1942 and the end of the reduction fishery in 1966, catch rates varied with herring availability. The average age of sampled fish increased, likely due to a steep decline in the percentage of age-3 fish.

Under management strategies since 1988, the average age of herring sampled from Sitka Sound increased, while the average age across the remaining eight stocks and Lynn Canal has remained relatively stable. In Sitka Sound, herring age composition since 1988 shows an increase in the percentage of age-9+ fish, and a decrease in the percentage of age-3 fish, although the wide variability in the percent composition of age-3 fish between 1988 and 1998 complicates interpretation. Compiled data from the remaining eight managed stocks and Lynn Canal shows a relatively stable trend with no significant change over time in the percent composition of both age-3 and age-9+ fish.

Maximum length and weight, mean weight-at-age

Maximum length or weight quantifies the depletion of larger fish in a population and may decrease as a fundamental response to the size-selective mortality caused by fishing (Nicholson and Jennings 2004; Shin et al. 2005).

During the years that the reduction fishery was operational and for which length data are available, the maximum length of sampled herring decreased slightly.

In Sitka Sound, increases were observed for both maximum length and weight from 1988 to 2011. The maximum length and weight for stocks in Lynn Canal and the other eight managed stocks outside of Sitka decreased slightly since 1988.

An increase in weight-at-age has also been associated with overfishing. The decline/collapse in stock abundance of three major herring fisheries - the southern North Sea, the Arcto-Norwegian and Hokkaido-Sakhalin stock - were all accompanied by a 25-50% increase in average weight-at-age as well as a decrease in age at first maturity (Motado and Hirano 1963; Dragesund et al. 1980; Ware 1985). In British Columbia, the average weight of an age-6 herring increased by 72% between 1949 and 1962, roughly paralleling the development of the North Coast fishery (Hourston 1980; Ware 1985). Again, food availability may confound interpretation of an increased weight-at-age corresponding to overfishing (Ware 1985: Schweigert et al. 2002). Growth and condition may reflect a complex interaction between density dependent effects, food supply and environmental variation, including plankton availability (Schweigert et al. 2002). However, while climatic variables may change all size-based indicators, the change does not appear to occur at the same magnitude as overfishing; temperature, for example, may have less of an effect on size structure than fishing (Blanchard et al. 2005).

In Southeast Alaska during the reduction fishery, the mean length decreased for both age-3 and age-7 fish and increases in mean weight are suggested. It is possible the decrease in mean length-at-age without a corresponding decrease in mean weight-at-age could indicate a compensatory response with reduced intraspecific competition resulting from exploitation.

In Sitka Sound stock since 1988, average weight-at-age increased for age-3 and age-7 herring with lesser increases in mean length. The trend in mean weight-at-age pooled across Lynn Canal and the eight major managed areas outside of Sitka Sound showed an increasing length-at-age for age-3 fish without a corresponding increase in weight for age 3 fish, and a decline in both weight-at-age and length-at-age for age-7 fish.

Age-at-maturity

Fishing pressure may indirectly lead to compensatory responses, with a reduction in stock biomass lessening intraspecific competition and potentially enabling faster growth and earlier maturation in species with a size-dependent maturity, such as herring (Stocker 1993; Law 2000). This shift towards maturation at earlier ages and smaller sizes may provide warning signals about changes in life history preceding more overt evidence of population decline (Trumble 1979; Olsen et al. 2004).

Time series on age-at-maturity data is available for herring sampled from Sitka Sound, Seymour Canal and Craig. In Sitka Sound, modeling indicates that no change in maturity occurred between 1980 and 2011. Data from Seymour Canal indicates an increase in the age at 50% maturity from approximately age 4.4 during 1980–1998 to age 5.6 during 1999–2011.

The opposite trend was apparent in herring sampled from Craig with progressively more fish maturing at younger ages in more recent years.

Spatial heterogeneity: appearance and disappearance of populations

Distribution of Pacific herring throughout Southeast Alaska changes seasonally. Spatial distributions may also shift with abundance, including a disappearance of populations that may suggest a species extinction risk (Powles et al. 2000; Hsieh et al. 2008). Geographic range may be significantly more important than local abundance in determining extinction risk (Harnik et al. 2012). Fishing may reduce areas of occupancy and spatial heterogeneity (Berkeley et al. 2004). Target species such as herring that aggregate in large numbers, that are consistent in time and space and are easy to find are readily overfished, leading to local depletions or extinctions (Vincent and Sadovy 1998; Reynolds and Jennings 2000). As populations decline, their geographical range also tends to decline as individuals seek and remain in the most favorable habitats, resulting in the extinction of local populations (McQuinn 1997). For example, the distribution of herring in Prince William Sound in the 1990s was greatly restricted to one region with dramatic declines in other areas (Brown et al. 2002). It is possible that, as the biomass of smaller spawning populations decreases with fishing, remaining fish join larger stocks where density-dependent increases in per capita fitness may induce a lower predation rate, increase foraging success, decrease environmental stress, and increase access to mates (Donahue 2006). In years of low herring spawning biomass, the distribution of larvae may also be affected (Swain and Wade 1993; Norcross and Brown 2001).

The current distribution of fishing in Southeast Alaska differs from that of the past, potentially due to the effects of historical fishing strategies and policies. In 1935, fishing grounds in Sitka Sound and Craig were considered the most productive and continue to contain large amounts of spawning herring. Spawning grounds centering around Juneau in Stephens Passage, however, were considered the third in importance and have since declined. Kootznahoo Inlet, once of great importance, declined by1935 (Rounsefell 1930; Rounsefell and Dahlgren 1935). Fishing occurred all over Southeast Alaska, but the most fish were removed from the Cape Ommaney area off the southern tip of Baranof (Skud et al. 1960) as evidenced by the multitude of fishing areas and reduction plants that were located in lower Chatham Strait (Fig.26).

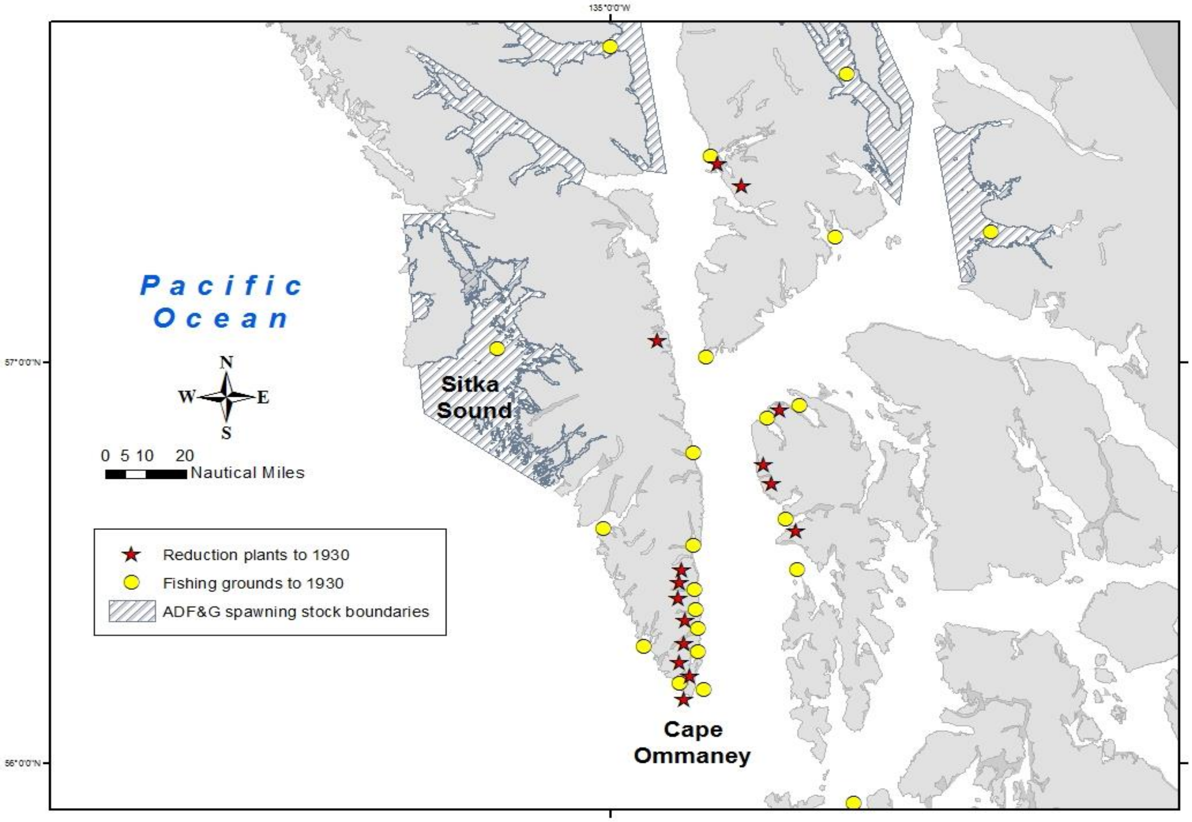


Figure 26. Fishing grounds and reduction plants around Cape Ommaney, pre-1930 (Rounsefell 1930).

As fish became scarce in one area, harvesting effort spread to other areas in order to maintain the level of catch, moving from the lower sections of Baranof Island into Sitka Sound, Icy Strait and Lynn Canal (Fig. 27).

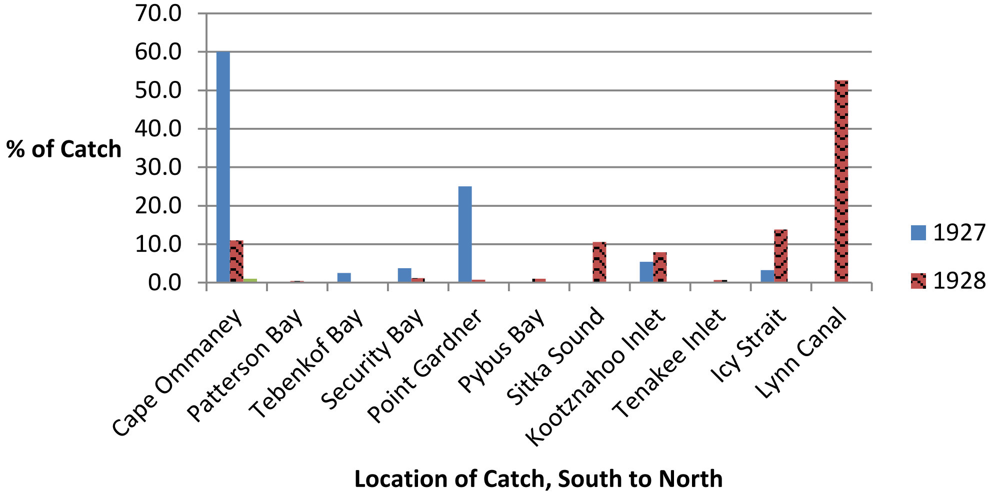


Figure 27. Percentage of catch from specific areas processed at the Killisnoo Plant, 1927 – 1928 (Rounsefell and Dahlgren 1935).

Large catches in 1939 from the Sitka region necessitated fishing curtailment and commercial fishing for non-bait herring was prohibited after August 2, 1939. Following industry objections, the prohibition was amended in 1940 to allow limited fishing, but no catch was obtained. Between 1941 and 1951, quotas were changed in response to fishing success in previous years, sometimes cut in half or closed completely due to poor herring abundance (Huizer 1952).

The biomass of herring removed during the reduction fishery was not significantly less than the combined biomass of stocks actively managed over the past several decades, especially if the biomass of Sitka Sound is excluded (Figs. 28 and 29).

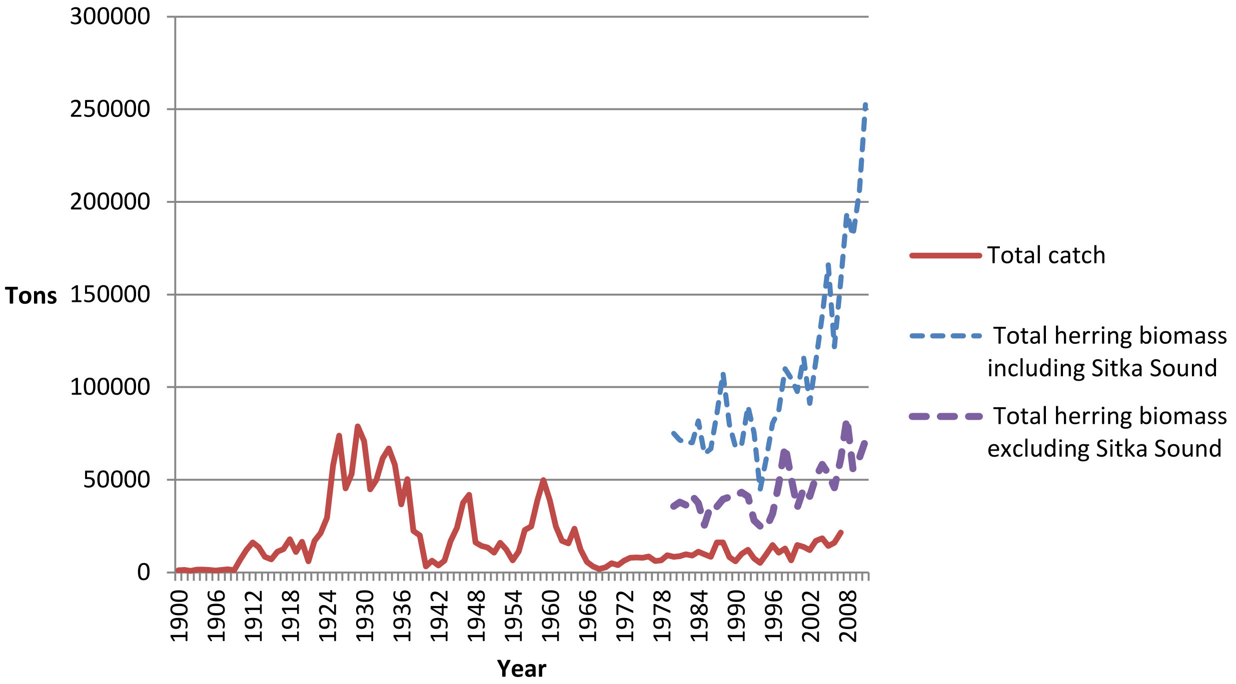


Figure 28. Combined herring biomass of nine ADF&G managed stocks, managed stocks less Sitka Sound and total recorded catch.

This relatively narrow difference suggests that herring stocks, at least in some regions, may still in the process of recovery from the reduction fishery. However, it is difficult to fully characterize the impacts of historical fishing on Southeast Alaska herring stocks for a number of reasons. Fishing efforts during the reduction fishery did not target all spawning grounds equally, tending to be more intense near reduction plants (Rounsefell and Dahlgren 1935), and historical records are not complete. Survey data collection was inconsistent, both in terms of methodology and locations/years surveyed. A disparity may also exist between resource agency data and users (Brown et al. 2002). Based upon historical reports and Traditional Ecological Knowledge (TEK) disappearance of herring from known spawning locations in Southeast Alaska, primarily as a result of the herring reduction industry, appears to have been more prevalent than reappearance or new colonizations (Fig. 30) (Skud 1959; Skud et al.1960; Thornton et al. 2010a).

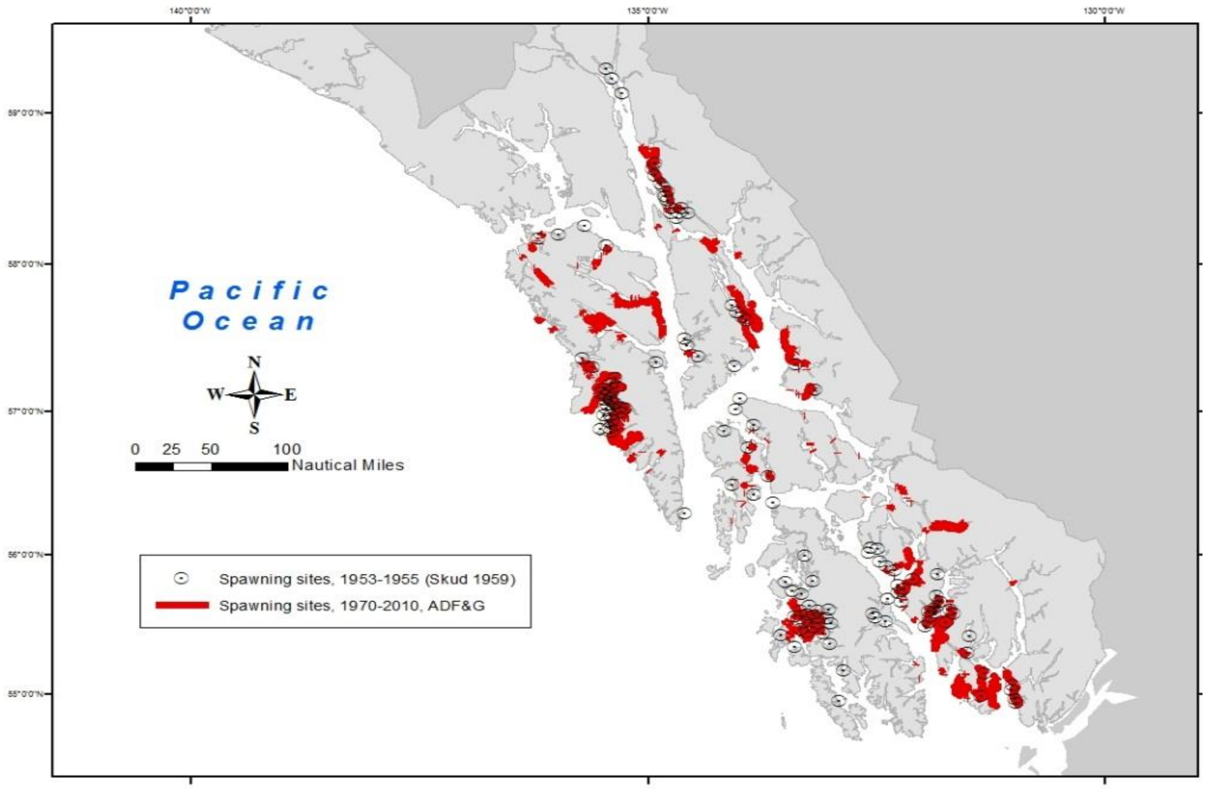


Figure 29. Herring spawning locations recorded in the early 1950's compared to spawning sites recorded under current management (Skud 1959; ADF&G).

Although no consistent systematic surveys have been performed to document changes, historical stocks are claimed to have been larger and spawning areas substantially more numerous (Brock and Coiley-Kenner 2009; Thornton et al. 2010a, 2010b). TEK reports include 2,759 miles of spawn (c.1915–present) as compared to 1,118 miles of spawn recorded by ADF&G during 1970–2007. While areas without spawn in ADF&G record may indicate areas that weren't surveyed rather than necessarily an absence of spawn, it has also been suggested that herring may be currently managed conservatively, but under a significantly depleted state (Thornton et al. 2010a, 2010b) with the biomass of herring available during the reduction fishery more indicative of the true AUB.

However, trophic cascades may also occur through the removal of large marine predators, with exploitation possibly leading to ecosystem shifts in top-predator or forage fish abundance (Laws, 1985; Merrick 1997; Cury and Shannon 2004; Bundy et al. 2009). It is possible that the commercial extirpation of whales and other marine mammal species from Southeast Alaskan in the early 1900s eased predation pressure on herring, allowing for a marked increase in herring biomass, which was then available to other predators, including the reduction fishery. For example, harvested whales species recorded in 1913 at Port Armstrong, approximately 15 km north of Cape Ommaney, included 73 sperm, 58 sulphurbottom, 32 finback, 21 humpback, 1 California gray and 1 bottlenose (N.B. the bottlenose possibly misidentified as the whale species is not found in the Pacific Ocean). Another 170 whales were harvested in 1914 (DeArmond 1997). While many of these whales were likely harvested in open water and herring may not be prey to all species, humpback and fin whales were recorded as present in inside waters (Andrews 1909). It is possible that the removal of large cetaceans from Southeast Alaskan waters facilitated an increase in herring abundance with a corresponding expansion in spawning locations. The depletion of Steller sea lions, another significant herring predator, throughout the early to mid-1900s may have also resulted in shifts in the herring biomass.

Overexploitation can lead to dramatic changes in community structure. While the exploitation rates, abundance and distribution of commercially important species may be well documented, the impacts of fishery-induced regime shifts on interspecific competition and predation are not well understood and may have unexpected and unpredictable consequences (Tsou and Collie 2001; Daskalov et al. 2007; Richardson et al. 2009).

6.2.4 Summary

Commercial fishing for herring in Southeast Alaska began predominantly with the reduction fishery which continued until the 1960s. Throughout this time, technological improvements and increased efficiency of the fishery lead to concerns about overexploitation, with the consequent establishment of catch limits. In the 1960s the volume of biomass removed by reduction industry was surpassed by the spawn-on-kelp fishery, which was then eventually surpassed by the sac roe fishery. Currently, the sac roe fishery removes over 90% of all herring harvested in Southeast Alaska.

A variety of indices may be used to define overfishing, including fishery and biological reference points.

- The ratio of fishing mortality to natural mortality ≤ .67 has been associated with sustainability in fishery management. In Sitka Sound, Seymour Canal and Craig since the 1980's, F/M ≤ .67 over 90% of the time.
- Abundance relative to threshold. Overfishing may be defined as harvest levels that drive abundance below a prescribed threshold. Since 1980, the percentage of managed stocks with estimated biomass above threshold levels has either remained consistent or increased.
- While it is not uncommon for the harvest levels to exceed the GHL, on average harvest levels have been fairly close to the GHL. Furthermore, exceeding the GHL does not generally lead to an exploitation rate that is greater than the maximum exploitation rate of 20%. Historically, exploitation rates, for both the harvest in Sitka Sound and the combined harvest of other stocks, have been substantially lower the 20% limit. Because forecast estimates are typically lower then hindcast estimates, exploitation rates and the GHL based on the forecast estimates tend to be more conservative. When harvest levels have been over 20%, generally this has been due to hindcast estimates which were lower than forecast estimates, have occurred rarely throughout the Southeast Alaska DPS.
- The trend in the combined biomass of Southeast Alaska managed herring has been increasing, with Sitka Sound herring markedly influencing the positive rate of growth.
- An increasing trend in combined recruitment of immature and mature age-3 herring is apparent in Sitka Sound and Seymour Canal. The combined number of immature and mature age-3 herring being recruited into the Craig stock has been decreasing slightly.
- Size based indicators may be used as indices for overexploitation. There is no evidence under current management that Southeast Alaska herring are exhibiting age truncation associated with depletion. Maximum length and weight has increased in Sitka herring, while slightly decreasing in other combined stocks. No marked trends are apparent in

weight-at-age or length-at-age data from Sitka Sound or other combined stocks. While age-at-maturity appears to be increasing over the last few decades in Seymour Canal, modeling of Craig herring indicated a trend towards earlier maturation and modeling of Sitka herring indicates no change in maturity over similar time periods.

- It is possible that the distribution and extent of spawning grounds as well as the abundance of herring throughout Southeast Alaska has decreased since the advent of the reduction fishery in the early 1900s. While it has been suggested that this discrepancy signifies that herring are currently being managed in a depleted state, other interpretations deserve equal consideration. First, all areas in southeast Alaska have not been surveyed within recent history and therefore records may not be complete. It is also possible that the extirpation of large whales, and to a lesser extent Steller sea lions, throughout Southeast Alaska (Section 6.3.2) may have significantly inflated the abundance of herring, which was then available to the reduction fishery.

6.3 Disease or Predation

6.3.1 Disease

Direct and indirect mortality from infectious and parasitic diseases affect abundance and demographics of marine fish populations, even when the causative agents are endemic within an ecosystem. However, quantifying population-level effects of disease in marine fishes, such as increased mortality or altered age structure, is challenging because: early life stages may be difficult to observe; the effects and the degree of disease mortality may go unnoticed due to the migratory nature of many fish species and subsequent difficulty in detection; and indirect mortality from impaired condition and avoidance behavior is poorly understood (Holst 1996; Mellergaard and Spanggaard 1997; Hershberger et al. 2007). Furthermore, because multiple pathogens often co-occur in populations, it may be difficult to ascribe causation. For example, confinement of wild Pacific herring often results in concomitant outbreaks of viral hemorrhagic septicemia virus Type IVa (VHSV), viral erythrocytic necrosis (VEN) and ichthyophoniasis (Hershberger et al 2006), the three most common diseases of herring in Southeast Alaska (T. Meyers, personal communication, 5/20/2010). Confined wild herring often undergo outbreaks of all 3 diseases, characterized first by viral hemorrhagic septicemia (VHS) which occurs as an acute disease that spreads quickly from relatively few carriers. Shortly thereafter, VEN manifests as a chronic and persistent disease that quickly spreads among confined herring (Kocan et al. 1997, 2001a; Hershberger et al. 2006). Herring with covert *Ichthyophonus* infections may die from concomitant viral disease epizootics, presumably because of stressor-induced exacerbation of pre-existing, chronic infections (Hershberger et al. 2006). Similarly, the failed recovery of herring in Prince William Sound has been linked to epizootics caused by several pathogens, most notably VHSVand *Ichthyophonus hoferi*, that have recurred in the population (Marty et al. 2010), although the magnitude and prevalence of specific pathogens has been debated (Elston and Meyers 2009).

The VHSV is endemic in multiple fish species throughout the northeast Pacific, including Pacific herring, eulachon, salmonids, and Pacific cod, and is periodically associated with population-scale epizootics (Meyers 1994; Meyers and Winton 1995; Hershberger et al. 2009; Hedrick et al. 2003). The first isolation of VHSV in Pacific herring followed an event in Prince William Sound; however, the virus has likely been endemic to the Pacific region for several hundred years (Einer-Jensen et al. 2004). Pacific herring are very susceptible to VHSV, and the disease is highly pathogenic to previously naïve individuals (Kocan et al. 1997). However, the portion of the population that survives their first exposure to VHSV becomes refractory to the disease, even after re-exposure to high levels of virus (Kocan et al. 1997; Kocan et al. 2001b; Hershberger et al. 2010), likely as a result of the a long-lived humoral immunity that confers a high degree of protection to disease survivors for extended periods (Hershberger et al. 2011).

The epizootics and associated mass mortality events from VHS are relatively common in the northeast Pacific. For example, in 1993, only a third of the expected herring population in Prince William Sound returned to spawn and of these, 15-43% had lesions consistent with VHSV infection (Kocan et al. 1997; Hershberger et al. 2007). The following year, a survey of free-ranging herring in Prince William Sound found a 4.7% prevalence of VHSV. In 1998, herring were considered the reservoir in a VHS epizootic involving herring, hake, and pollock in Lisianski Inlet near Pelican, AK. No other pathogens were associated with the mass mortality and no environmental catalyst was apparent (Meyers et al. 1999). Conditions predisposing wild populations of Pacific herring to VHS epizootics include:

(1) a preponderance of highly susceptible individuals and lack of herd immunity;
(2) high infectivity and transmissibility of the virus (P. Hershberger, personal communication, 11/3/2010).
(3) sufficient virus stability in seawater to allow fish-to-fish transmission (Kocan et al. 2001a; Hawley and Garver 2008);
(4) high viral shedding rates from infected hosts (Kocan et al. 1997, Hershberger et al. 2010);
(5) water circulation patterns that concentrate the exogenous viral stage;
(6) low water temperatures resulting in increased virulence; and
(7) gregarious host social behaviors that are conducive to horizontal transmission (Hershberger et al. 2010).

These environmental conditions are easily replicated in laboratory tanks, spawn-on-kelp net pens, or bait herring pens, where the capture and confinement of wild herring, demonstrating covert VHSV infections, often results in inducible VHS epizootics (Hershberger et al. 1999; Kocan et al. 2001a). Although VHSV is conventionally considered highly virulent in Pacific herring, causing rapid disease and high mortality, new research indicates that the disease can also manifest in a more chronic form, characterized by lower and more prolonged mortality and the presence of persistent viral carriers in the exposed population for durations as long as 6 months post-exposure (Hershberger et al. 2010a). This mechanism of viral persistence provides new insights into carrier hosts in the northeastern Pacific that may serve as virus reservoirs capable of perpetuating VHS until host and environmental conditions become conducive for the next epizootic.

Viral erythrocytic necrosis (VEN) is a chronic disease of Pacific herring caused by a putative iridovirus. Similar to VHSV, localized VEN epizootics often occur after the capture, transport, and confinement of Pacific herring. VEN epizootics have been reported in Puget Sound, Prince William Sound, and Southeast Alaska (MacMillan and Mulcahy 1979; Meyers et al. 1994; Hershberger et al. 2009). The first report of VEN in Alaska and the first recorded epizootic associated with the disease occurred in a mass mortality event in Southeast Alaska from May to early July in 1985. This epizootic was associated with large-scale juvenile fish kills in 3 separate locations near Ketchikan. Exacerbating stressors, at least in one of the locations, were thought to include extreme osmoregulatory distress because of low environmental salinity, overcrowding, and predator harassment (Myers et al. 1986). Additional VEN epizootics in herring from Southeast Alaska were reported in 1989, 1994, and 2001 (Hershberger 2009 from T.R. Myers, unpublished accession reports) and were associated with of mass mortalities and signs of morbidity. Herring from Puget Sound also exhibited VEN epizootics from 2005 to 2007, with peak prevalence of 67% in 2005. The epizootic involved primarily herring from the age-0, 2005 year class, and infection prevalence waned to near zero a year later. A second outbreak in 2007, with a peak intensity of prevalence of 88%, involved both age-1 juveniles and later age-0 newly metamorphosed juveniles. Unlike Southeast Alaska, the Puget Sound epizootics were detected through routine health surveys of wild fish and not during a mass mortality event. The subsequent disappearance of the affected age cohorts, either through death or recovery and migration, provided evidence of population-level impacts. It was hypothesized that VEN may result in chronic mortality of juvenile herring with development of resistance among survivors (MacMillan and Mulcahy 1979; Hershberger et al. 2009), unless suboptimal environmental conditions exacerbate the disease leading to acute mortality (Hershberger et al. 2009). Detection of these chronic epizootics with the apparent absence of acute mortality events suggests that VEN and other diseases result in cryptic mortalities that, although important as population-limiting factors, are easily overlooked without routine fish health surveillances in wild populations.

Ichthyophonus hoferi is an internal Mesomyceozoean parasite that infects many species of marine fish. The parasite has been associated with several massive epizootics and population-level impacts in wild marine fishes. The parasite is commonly detected in Pacific herring, with infection prevalence increasing directly with age class from 5 to 6% in age-0 fish, to 24% in age-1 fish, and 50 to 70% in fish over 2 years old (Kocan et al. 1999). In British Columbia, prevalence ranged from 10.5 to 52.5% in 2000 and 2001 with a variation in prevalence noted between stocks (Jones and Dawe 2002). Infection rates ranged from 17 to 55% in Puget Sound herring during 2000, and from 5 to 29% in Prince William Sound herring between 1993 and 1994 (Marty et al. 1998); however, diagnostic techniques differed between the two geographic studies, making direct comparisons difficult. It was postulated that *I. hoferi* infection may reduce mean age of adult herring due to a higher epizootic prevalence in older herring (Hershberger et al. 2002). A study in Prince William Sound during 1994 - 2000 found a consistently high prevalence of *I. hoferi*, which increased with each year-class within individual life spans. While VHSV is thought to contribute greatest mortality to young fish, mortality from *I. hoferi* targets older cohorts in a population (Marty et al. 2003). Along with the population age structure and location, the prevalence of *I. hoferi* may also vary with the season. Juvenile herring in Prince William Sound were also found to experience higher rates of energy loss over winter, potentially due to the energetic costs of coping with disease. If energy stores are insufficient to meet biological demands, increased mortality and poor recruitment may result (Vollenweider et al. 2011b). Because herring do not appear to be able to clear infection from *I. hoferi*, the seasonal decline in prevalence from spring through autumn most likely reflects a selective mortality among infected cohorts (Hershberger et al. 2012).

ADF&G does not perform on-going, random testing for the presence of disease in Southeast Alaskan herring. Barring epizootics, the current baseline prevalence is assumed to range from 0 to 0.8% for VHVS, 0 to 5% for VEN and 10 and 40% for *Ichthyophonus*. Prevalence variation is likely a function of stressors acting upon the population, such as with increased VHSV prevalence of 21.1 to 79.2% in herring pounds (T. Meyers, personal communication, 5/20/2010).

Disease manifestation results from complex interactions among pathogen, host, and environment, with pathogenicity in nature depending on factors such as age, predation, nutritional status and exposure to environmental conditions (Kocan et al. 1999). Potential synergy and overlap of diseases may also confound both exposure as well as interpretation of findings. Although the epidemiological course for a suite of diseases varies, laboratory studies indicate that application of natural stressors may contribute to disease epidemics in wild herring populations resulting in decreased fitness and increased mortality (Meyers et al. 1994; Hershberger et al. 1999; Kocan et al. 2001b; Hedrick et al. 2003). Poor body condition in Prince William Sound herring, for example, whether from insufficient prey or warmer water temperatures, was considered an underlying risk factor for multiple epizootics (Marty et al. 2003). Given the proper circumstances, disease has the potential to be a significant limiting factor for herring populations (Kocan et al. 1997), perhaps especially as a co-occurring stressor, and should not be dismissed as a major constraint limiting age structure and survival of Pacific herring (P. Hershberger, personal communication, 11/3/2010).

6.3.2 Predation

Pacific herring play a vital role in the life history of many marine predators. Predation is a consistent source of mortality through all life stages of herring and may be the dominant source of mortality for some cohorts (McGurk 1989; Stokesbury et al. 2000, 2002; Tyrell 2008). While assessing trophic level interactions is essential to accurately describe the current status of herring, it is also imperative to recognize that predation relationships are dynamic (Aydin et al. 2007). Herring in Southeast Alaska may be part of an ecosystem that exhibits a “wasp-waist” structure, with herring as the constricting species in the middle directing trophic dynamics both “top down” as prey and “bottom up” as predator. Attributes of these mid-level species may include the ability to mobilize and relocate according to their own internal dynamics and preying upon the early life stages of their predators which may contribute to an unstable feedback loop in the trophic system (Cury et al. 2000). Populations of herring stocks may also follow a “predator pit” dynamic (Fig. 31), with features including: a refuge from predator interest when abundance is very low; significant predation when abundance is sufficient to attract interest but not sufficiently high to satiate predator demands; and a significant increase in abundance when predation is satiated (Bakun, 2006). A cofounding feature of predator/prey interactions involving herring include the seasonal aggregations of herring in dense schools which may still attract predators even at low herring population levels. In some systems, predation by cetaceans has been suggested to delay recovery of depleted herring stocks (Sissenwine et al. 1984; Rice et al. 2011) and this may be an indication of a predator pit dynamic.

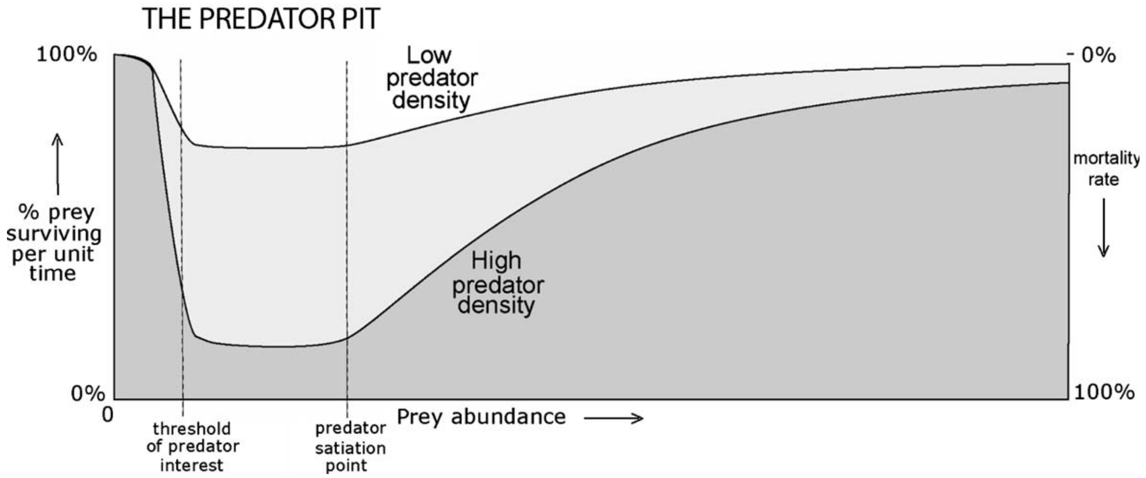


Figure 30. Diagram of the predator pit dynamics (Bakun 2006).

The impact of predation on herring populations may be significant, potentially exceeding mortality from commercial fishing. In a multispecies virtual population analysis of the effects of 14 key predators on Atlantic herring from 1982 to 2002, the annual average biomass consumed by these predators was 3 to 5 times higher than the biomass removed through commercial landings (Tyrell et al. 2008). In the eastern Bering Sea, predation by groundfish, marine mammals and birds on Pacific herring was assessed between 1985 and 1988. The total biomass removed by predators, excluding cetaceans, was estimated to be over twice the biomass removed through commercial fishing (Livingston 1993). With respecxt to predation by cetaceans, humpback whales in Prince William Sound, Alaska may have consumed up to 13,000 tonnes of herring in 2008 compared to the last commercial harvest of 4,000 tonnes. The guideline harvest level set in the commercial fishery varied from 15 to 20% of the herring biomass, whereas cetacean predation intensity ranged from 11 to 77% (Rice et al. 2011).

The distribution of some marine predators may be explained solely or in part by the presence of herring (Sveegaard et al.2012) and shifts in herring biomass may also impact the abundance, distribution, and species composition of predators. Models of trophic relationships in Georges Bank from 1978 to 1992, including six predators and herring as an important prey species, found that predator diet shifted from other species to herring as herring became more abundant. Average annual consumption of herring by four predator groups (demersal fish, marine mammals, large pelagic fish and seabirds) increased from 58,000 tonnes average in the late 1970s to 310,000 tonnes from 1998 to 2002. Of these groups, demersal fish consumed the most herring overall; however, by 2002, marine mammals were consuming the greatest number of herring, with the heaviest impact from humpback whales and fin whales (Overholtz and Link 2007).

Many different predators exploit herring through various life history stages. Along coastal North America, spawning events alone have been associated with at least 25 different bird and marine mammal species which prey upon herring, with some of these species eating only eggs, some eating only adults and some targeting multiple life history stages (Willson and Womble 2006). In Southeast Alaska, members of many taxa prey upon herring at different times, including mammals, birds, fish and a variety of invertebrates.

6.3.1.1 Marine mammals

Cetaceans

Between 1991 and 2007, surveys conducted throughout Southeast Alaska inland waters identified seven different cetacean species (Dahlheim et al. 2009). Although herring may be considered an important prey item for the majority of these species (Gannon et al. 1998; Reeves et al. 2002; Wynne 2007), including fin whale, minke whale, harbor porpoise, Dall's porpoise and Pacific white-sided dolphin, most are either too sporadic, of insufficient abundance or insufficiently characterized to determine their significance as Southeast Alaska herring predators (Dahlheim et al. 2009; Allen and Angliss 2011). Although herring have also been recorded as a major prey species for some killer whales (Simila et al. 1996), the transient killer whales of Southeast Alaska feed almost exclusively on pinnipeds, cetaceans, and seabirds, and the resident killer whales feed primarily on salmon and have not been associated with large seasonal concentrations of herring (Ford et al. 1998; Ford and Ellis 2006). Limited evidence suggests that fin whales, which were present in Southeast Alaska before commercial harvesting, may have consumed a substantial amount of herring. A 1907 account of fin whale stomach contents includes one whale that had eaten "an enormous quantity of herring (*Clupea pallasi*); four barrels…" (Andrews 1909). Aside from sightings in lower Clarence Strait (Dahlheim et al. 2009), fin whales are no longer commonly found in Southeast Alaska. The population of humpback whales, however, has experienced a resurgence since the commercial harvest stopped in 1966. Humpback whales are currently the largest and most widespread cetacean in Southeast Alaska and herring are a primary prey species.

Humpback Whales

The humpback whale is the most common whale species in Southeast Alaska, and the most significant cetacean predator of Southeast Alaska herring. Approximately 20,000 humpback whales are found throughout the North Pacific, with whales in Southeast Alaska and northern BC exhibiting strong seasonal site fidelity and composing a discrete feeding aggregation of approximately 3,000–5,000 individuals. This aggregation primarily uses waters around the Hawaiian Islands for mating and calving, with most individuals migrating annually between Hawaii and the northern feeding areas (Calambokidis et al. 2008). Although migration timing varies among individuals, most whales depart for Hawaii in fall or winter and begin returning to Southeast Alaska in spring, with continued returns through the summer, giving a peak occurrence in Southeast Alaska during late summer to early fall. However, there are significant overlaps in departures and returns (Baker et al.1985; Straley 1990). In addition, some whales have remained in Southeast Alaska throughout the year (Straley 2000; Rice et al. 2011).

Following over half a century of whaling in the North Pacific which ended in the 1960s, the humpback whale population in Southeast Alaska has grown significantly over the last 40 years. Although humpbacks were undoubtedly taken by less efficient whaling methods in prior years, modern whaling with harpoon cannons mounted on catcher boats began in Southeast Alaska in 1905 (Rice 1978). Three commercial whaling companies existed in Southeast Alaska to support the local whaling industry with the last, located at Port Armstrong, closing in 1919 (DeArmond 1997). The last whale harvest in Southeast Alaska occurred in 1922, although whaling continued in BC until 1963 (Rice 1978). Commercial harvest of humpback whales was banned by the International Whaling Commission in 1966 and the whales were listed as endangered under the Endangered Species Act in 1970. Since then, humpback whale numbers of the North Pacific population have increased by 4 to 8% annually (Calambokidis et al. 2008; Barlow et al. 2011). In Southeast Alaska, the median rate of increase was estimated at 5.1% with a median abundance estimate of 1585 whales in 2008 (Hendrix et al. 2012). Humpback whale predators include killer whales and possibly tropical sharks (Clapham and Mead 1999; Steiger et al. 2008).

Humpback whales are baleen whales in the rorqual family (Balaenopteridae). Up to 16 meters long, humpback whales have ventral pleats which allow for the expansion of the throat when capturing prey. Prey are taken into the mouth with large quantities of water then filtered through baleen plates and swallowed. In Southeast Alaska, primary prey species include euphausiids (mainly *Thysanoessa raschii* in inside waters) and small schooling fishes such as capelin, Pacific sand lance, walleye Pollock, and Pacific herring (Wing and Kreiger 1983; Kreiger and Wing 1984, 1986; Straley 1990). Humpback whales both prey upon herring and compete with herring for zooplankton.

Pacific herring are an extremely valuable, energy rich food source for humpback whales in Southeast Alaska throughout much of the year. Of the dominant forage fish species in Southeast Alaska, the Gulf of Alaska and Prince William Sound, herring are among the prey with the highest energy content (Anthony et al. 2000; Iverson et al. 2002; Vollenweider et al. 2011), with body fat content in adult fish up to 21% (Iverson et al. 2002). However, among 16 forage fish species examined in Southeast Alaska, the energy content of herring was also the most variable. Energy content in herring varied seasonally and generally increased over the summer, peaked in autumn or winter, and declined to a minimum in spring or early summer (Vollenweider et al. 2011). Although whales target herring during spawning events in the spring (Straley 1990; Willson et al. 1998), consumption of herring tends to peak in fall or winter. The life history of herring includes aggregation at a time when energy content is highest, providing the whales access to an energy rich and accessible food source in the fall and winter prior to migration. It has been postulated that some whales linger in Alaska or forego migration altogether due to the availability of herring (Baker et al.1985; Straley 1994; Straley et al. 2009a).

The volume of biomass consumed by cetaceans depends upon daily per capita consumption, diet composition, the number of foraging animals, and foraging period (Overholtz and Link 2007). Daily consumption by baleen whales in the Northeast U.S. continental shelf has been estimated to range from 40 to 2000 kg/day, with intermediate values approximated at 100-600 kg/day (Col at al. 2012). Humpback whales around Kodiak, Alaska, were found to consume an estimated 370 kg/day (Witteveen et al. 2006). However, the overall impact of prey consumption by whales ultimately depends on the number of whales foraging on herring in a particular location for a specific period of time, which depends upon variables such as whale abundance and the relative abundance and availability of herring and other prey species.

In Southeast Alaska, humpback whales are found throughout all major waterways and in a variety of habitats, including open-ocean entrances, open-strait environments, near-shore waters, areas with strong tidal currents and secluded bays and inlets. The whales consistently concentrate in several locations in Icy Strait, Lynn Canal, Stephens Passage, Chatham Strait, and Frederick Sound with lesser historical presence in Sumner and Clarence Strait (Baker et al.1985; Straley et al. 1995; Dahlheim 2009). These patterns of occurrence likely follow the spatial and temporal changes in types, densities and distribution of prey (Bryant et al. 1981; Baker et al. 1985; Kreiger and Wing 1986; Baker et al.1992), and the presence of whales may reflect local prey abundance and availability.

Stomach contents of humpback whales taken during the spring and summer of 1908 from whaling stations near Vancouver Island and on southern Admiralty Island in Southeast Alaska, contained mainly euphausiids, although one humpback stomach contained a large quantity of a cod species (Andrews 1909). These observations likely reflect seasonal availability of prey. Although prey density may be a factor in determining foraging location, some humpback whales have shown a preference for certain prey items and have continued to feed on herring in Icy Strait when other whales have shifted to euphausiids in Frederick Sound (Kreiger and Wing 1986; Baker et al. 1992). Although euphausiids in Seymour Canal support the largest known fall and winter aggregations of Southeast Alaska humpbacks, herring may also support whale aggregations in late fall and early winter (Straley 1990; Baker et al. 1992). An increase in herring in Sitka Sound during the late 1980s and early 1990s was believed to trigger a similar, although slightly lagged, increased humpback whales presence, with whales immigrating primarily to capitalize on the availability of overwintering herring (Straley 1994).

Humpback whale predation on the biomass of herring in Southeast Alaska is a fluid and complex process depending, in part, upon location, season, and individual whale preference. Temporal and spatial variability in the abundance of herring and alternative prey species, including winter aggregation in specific areas, significantly affects the impact of humpback predation on herring populations. In a two year comparative study, the fall and winter patterns of humpback whales foraging on herring in Prince William Sound, Lynn Canal, and Sitka Sound were markedly different with respect to whale abundance, seasonal trends, and dietary composition (Rice et al. 2011).1980

Prince William Sound contained the largest number of whales foraging for the longest period of time, and consequently removing the greatest portion of herring biomass. Whales present in Prince William Sound until mid-winter were strongly associated with large schools of herring. In Lynn Canal, the presence of whales was also strongly associated with large schools of herring, although whale abundance peaked in fall and fewer individuals were observed. The number of whales decreased through winter. As winter progressed, herring abundance increased and the remaining whales foraged more intensely on herring. In Sitka Sound, seasonal trends in abundance were similar to Lynn Canal, except that more whales were present into the winter of 2008/09. Whales in Sitka Sound foraged primarily on krill in the fall, but as whale numbers declined entering winter, the remaining whales shifted to herring. The decline of whales in Lynn Canal and Sitka Sound was followed by an increase in Seymour Canal and Frederick Sound, generating speculation that whales of Southeast Alaska use wintering herring as an intermediate food source until euphausiid aggregations become available later in the year. The greater magnitude of foraging on herring in Prince William Sound could result from an absence of alternative, high lipid prey. Consequently, the magnitude of foraging in Prince William Sound proved to be a dominant top down force in herring removal. Based upon a resting metabolic rate, whales solely consuming herring could remove from 18 to 23% of pre-winter herring biomass in the area, at a minimum encompassing the guideline harvest level of 15-20% for a commercial fishery or the natural mortality factor used in the stock assessment modeling. While this magnitude of humpback predation could contribute to delayed recovery in depressed herring populations, as in Prince William Sound, substantial uncertainty remains around the predation estimates, the extent to which whale predation adds to other natural mortality factors, and whether total mortality is sustainable (Rice et al. 2011).

Although historical whale abundance may be estimated using current trends and historic catch values (Witteveen et al. 2007), significant ecological changes in Southeast Alaska confound the use of historical population estimates to determine current carrying capacity of humpback whales (DeMaster et al. 1996). However, under current conditions, there is some indication that the humpback whale population in Southeast Alaska may be nearing carrying capacity. Discovery of new humpback whales associated with Sitka Sound has reached a plateau. Each year fewer and fewer new whales are observed and, as of 2008, the total known whales (557) was neatly contained within the 95% confidence interval (346,699) for the estimated humpback whale abundance (Fig. 4) (J. Liddle, personal communication, 11/8/2011).

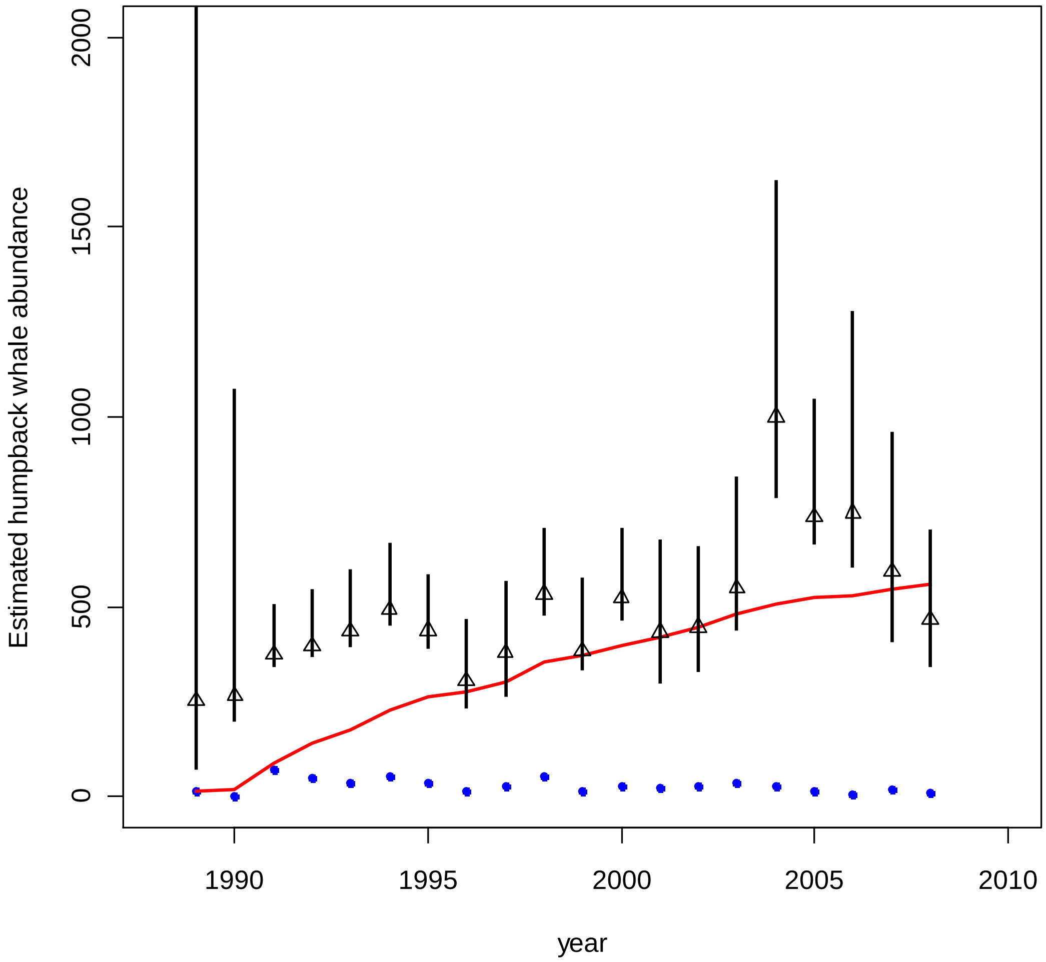


Figure 31. Abundance estimates with 95% confidence intervals of humpback whales associated with Sitka Sound (black), cumulative total of unique whales by year (line) and newly discovered unique whales by year (dots) (J. Liddle).

Pinnipeds

Pinnipeds are also likely to be significant consumers of herring (Bowen 1997). On a global scale, modeling of trophic interactions between marine mammals and fisheries indicates that the highest overlap occurs between fisheries and pinnipeds and dolphins rather than large cetaceans (Morissette et al. 2012). In Southeast Alaska, Steller sea lions are increasing in number and consequently may be the most prominent pinniped species that rely on herring.

Steller Sea Lions

The Steller sea lion is the largest member of the eared seal family (Otariidae) and found throughout much of the northern Pacific Basin. In 1997, the population was delineated into two distinct population segments, with sea lions of Southeast Alaska, California, Oregon, and British Columbia to the 144^{o} West longitude encompassing an " eastern population". Predator control and bounty hunting contributed to the low abundance of the eastern population during the first half of the 20th century. In Southeast Alaska, one of the earliest population estimates, although of unknown accuracy, was 50 to 100 animals at the Forrester Island rookery in the 1920's. From the 1920's until the 1980's, the Forrester Island complex was the only rookery in Southeast Alaska. At present, five rookery sites are spread along coastal Southeast Alaska and, between the 1970's and 2002, the regional population has experienced an annual increase of approximately 3.1% (Pitcher et al. 2007).

The foraging strategy of Steller sea lions is strongly influenced by seasonality of both sea lion reproductive activities and the ephemeral nature of many prey species. Steller sea lions in Southeast Alaska are considered opportunistic foragers that will relocate based upon seasonal prey availability. In general, sea lions forage on herring aggregations in winter; in spring on spawning fish, including herring and eulachon; and throughout the year, on various other species, including herring (Winship and Trites 2003; Sigler et al. 2009; Womble et al. 2009). The most commonly identified prey items in Southeast Alaska included herring, walleye pollock, sand lance, salmon, arrowtooth flounder, rockfish, skate, squid, and octopus. Between May of 2001 and March of 2004, sea lion scat samples were collected quarterly from haulouts in Frederick Sound. Of 59 different prey species identified in these samples, the frequency of herring ranged from 31% in the fall to 39% in the winter (Trites et al. 2007). As pollock, herring, and hake were the most abundant species in the pelagic habitat, researchers postulated that the sea lions were selecting dietary items relative to abundance in the environment (Sigler et al. 2009; Csepp et al. 2011). However, researchers also determined that sea lions may sometimes travel greater distances to access energy rich forage fish such as herring, even though other prey species may be abundant nearby, or sea lions may sometimes select less nutritious fish if they are located closer to the haulouts (Sigler et al. 2009). Scat samples collected during 2001–2004 from Benjamin Island contained 56 prey items. The most common prey were herring (Frequency of Occurrence, or FO, =90%) and pollock (FO=88%) with a high co-occurrence of herring and pollock in the scat. Though a wide size range of prey species was consumed, the sea lions showed a preference for prey within the 10 to 35 cm (fork length) size range, with a strong selectivity for 14 to 22 cm herring, which were favored even when smaller herring dominated the nearshore surveys (Sigler et al. 2009). Adult herring also predominated (FO=96%) in scat collected from Benjamin Island, with fork lengths ranging from 11 to 35 cm, overlapping the herring sizes observed in acoustic surveys (Womble and Sigler 2006). Seasonal changes in the presence of herring were also found to coincide with seasonal changes in Steller sea lion abundance, especially evident during periods of aggregation. The frequency of herring in the sea lion diet in Benjamin Island scat samples corresponded to the overwintering herring biomass availability and the numbers of Steller sea lions in the area; the frequency of herring in the diet decreased with herring dispersal (Womble and Sigler 2006). Sea lions appear to show a numerical response to prey abundance; that is, a greater number of sea lions are present when prey is more abundant (Womble et al. 2005; Womble and Sigler 2006; Sigler et al. 2009). In Prince William Sound during the extended winter period, Steller sea lions were found to target herring extensively and almost exclusively (Thomas and Thorne 2001, 2003). The sea lions foraged selectively on Pacific herring, possibly due to the shallow distribution of herring at night, compared to the more abundant, but deeper and less accessible, walleye pollock (Thomas and Thorne 2001).

The foraging strategy of Steller sea lions, therefore, appears to be finely tuned to fulfill complex physiological requirements and relative energy demands (Sigler et al. 2004; Womble et al. 2005). In assessing physiological energy partitioning and consequences to fitness, researchers found that Steller sea lions fed herring during both winter and summer adapted better to prevailing natural conditions than animals fed a lower energy diet of walleye pollock (Du Dot et al. 2008). In Upper Lynn Canal, the average energy density of pelagic prey, primarily herring overwintering in areas such as the Amalga Trench (Sigler and Csepp 2007), was almost an order of magnitude greater in winter months than during other times of the year, corresponding to the greatest usage of the nearest sea lion haulout at Benjamin Island (Gende and Sigler 2006). Herring represented an average of 81% of the total energy available to sea lions in Lynn Canal, including an average of 99% between November and February (Sigler and Csepp 2007). Clearly, Steller sea lions depend upon herring as an essential high energy food source.

The overall impact of Steller sea lion predation on the Southeast Alaska herring biomass depends upon the complex variables of both predator and prey life histories and accurate quantification is difficult. The estimated 1998 total prey biomass consumed by Steller sea lions in Southeast Alaska ranged from 121,000 to 140,000 tonnes with forage fish, principally herring and sand lance, composing from 12% of the diet in autumn to 22% of the diet in the summer. Food requirements, and consequently consumption, varied greatly with energy content of prey species and season. A range of maximum daily food requirements for Steller sea lions in Southeast Alaska was estimated, with the highest requirement of 40 to 46 kg for a pregnant 10 year old female nursing a pup in May (Winship and Trites 2003). Estimated prey consumption in Frederick Sound for all sea lions was 2,200 tonnes/month with daily individual consumption estimated at 19 kg. Monthly consumption was lowest in June and July and highest in September, again reflecting the abundance of sea lions and availability and energy density of prey items (Sigler et al. 2009).

Sources of mortality for Steller sea lions are primarily predation by killer whales and sharks and anthropogenic causes such as illegal shooting, subsistence harvest and incidental fisheries mortality (Loughlin and York 2000).

6.3.1.2 Birds

A multitude of bird species have been identified as herring predators including both marine species and terrestrial species such as geese, crows and bald eagles (Bayer 1980; Haegele and Scheigert 1989; Bishop and Green 2001; Sullivan 2002; Willson and Womble 2006). Birds utilize a variety of foraging strategies in their dependency upon herring and herring roe and may change both habitat use and diet in an active response to the presence of herring (Munro and Clemens 1931; Zydelis and Esler 2005). The distribution of these avian predators tends to be stratified and localized, reflecting a preference for herring age or size class (Haegele 1993), and birds will also often forage for herring in complex mixed species assemblages, with each avian species playing a unique and consistent role in the process (Chilton and Sealy 1987). Seabird assemblages associated with herring spawn in Prince William Sound, for example, are dominated by glaucous-winged gulls, mew gulls, surf scoters, surfbirds and black turnstones (Bishop and Green 2001), although other species such as pelagic cormorants, common murres and marbled murrelets are also fairly common. In British Columbia, at least 21 bird species eat Pacific herring or their eggs (Haegele 1993; Vermeer et al. 1997**).**

The presence of various bird species has been highly correlated with herring abundance and life history, especially in relation to spawning events. Along much of the Pacific Coast of North America, the ephemeral presence of herring spawn each spring generates dramatic congregations of birds. On the east coast of Vancouver Island, the number of in-shore and off-shore birds observed in 1998 was 48 times greater during the herring spawning period than during the pre-spawn period. In Lambert Channel, British Columbia, a pre-spawn estimate of 227 birds increased to 23,133 birds during active spawning, followed by 2,067 birds during the late larval stage. Mean bird density among sites went from an average of 66 birds/km^2 during the pre-spawning period up to 616 birds/km^2 during spawning (Sullivan et al. 2002). In Southeast Alaska, bird predation on herring spawn has been considered heavy, such as the estimated 13,000 herring and glaucous-winged gulls and 16,000 surf scoters noted feeding on herring during a spawning event at Kah Shakes-Boca de Quadra in 1977 (Blankenbeckler and Larson 1978a). Similar aggregations have been noted in other locations around Southeast Alaska (Speckman et al. 2003) and British Columbia (Sealy 1975; Carter and Sealy 1990; Burger 2002).

During these spawning events, birds may efficiently utilize different foraging strategies. In British Columbia and Washington, bird species displayed specialization to various stages of herring with, for example, loons being the most plentiful when adult fish were schooling offshore; gulls, grebes and cormorants targeting adult fish in the shallows; and diving ducks, mew gulls and black turnstones feeding on roe (Grass 1973; Sullivan et al. 2002). Birds may also use different locations and strategies to obtain herring spawn throughout the intertidal and subtidal zones. Egg deposition at the higher intertidal zone was found to increase egg predation by gulls (Munro and Clemens 1931). At lower deposition sites in the intertidal zone, avian predator diversity was greater. Gulls foraged either while swimming or standing near the tideline, scoters accessed most spawn through diving, and black turnstones or surfbirds were limited to exposed areas above the tideline (Bishop and Green 1999). Easy availability of herring eggs may increase energy intake while decreasing foraging time relative to other prey species, possibly allowing for necessary social behaviors, such as courtship and pair formation (Munro and Clemens 1931; Rodway et al. 2003; Zydelis and Esler 2005). For example, surf scoters and white-winged scoters decreased their dive rates by 70% and spent approximately 50% less time foraging when feeding on roe (as opposed to their normal winter diet of bivalves), allowing for increased energy efficiency and time for premigratory courtship (Lewis et al. 2007).

Avian predation on roe during spawn events may be significant, with mortality estimates ranging from 3 to 87% depending upon the number of birds present as well as the location and magnitude of the spawn. In a 1994 study over 27 days in Prince William Sound, five bird species consumed a herring egg biomass estimated at 857.1 metric tons or, depending upon the formula for estimating egg availability, between 18 and 31% of the total available volume of eggs (Bishop and Green 2001). On the west coast of Vancouver Island, avian predation, primarily by gulls, was considered the greatest and most significant source of egg loss, averaging 39% (range 30-55) of the deposited spawn (Outram 1958). In San Francisco Bay, the gull predation rate on herring spawn exposed at low tide (50% of total deposition) ranged from 83 to 87% (Spratt 1981). A survey of egg loss from Barkley Bay in British Columbia during a 1988 spawning event estimated a 4% removal of the total deposition by birds (Haegele and Schweigert 1989). As expected, the impact of avian predation depends, in part, upon the volume of spawn deposition. In years of abundant and heavy spawn, birds in the Strait of Georgia consumed only 3 to 4% of egg biomass. However, in years with low spawn deposition and high bird abundance, avian predation can significantly affect egg survival to the larval stage. At a 1975 spawning event in northern British Columbia, 300,000 surf scoters removed up to 70% of the spawn (Haegele 1993). During a period of low spawn availability in Puget Sound, egg hatching success in sites protected from bird predation was estimated at 62%. In sites available to birds, primarily scoters and scaup, the hatching rate ranged from <1 to 6% (Cleaver and Franett 1946). In another Puget Sound study, conducted during low herring abundance, daily egg loss from avian predation was estimated at 20-50% (Palsson 1984). The concentrated nature of herring spawn may lead to high egg losses, even during periods of low spawn biomass, which may in turn drive herring abundance even lower (Rooper and Haldorson 2000).

While spawn events may attract the greatest number of birds resulting in the most significant impact to biomass, other herring life history stages are also prone to avian predation. In a study investigating the impact of piscivorous birds on forage fish off Vancouver Island, seabirds consumed an average of 16% of the juvenile herring biomass during 1991-1993 (Logerwell and Hargreaves 1997). In Prince William Sound, the winter distribution of many bird species responded to the presence of adult herring schools (Thomas and Thorne 2003). As a group, marine birds represented a substantial source of herring mortality in Prince William Sound, consuming an equivalent of 2.7 – 10.1% of the total adult herring biomass and up to 3,134 tons of the juvenile herring biomass in a given winter (Bishop et al. *submitted*).

Interspecific specialization may also occur between birds and marine mammals when preying upon herring. In Prince William Sound, for example, a variety of birds and marine mammals nocturnally feed on herring that migrate to the surface at night, both inshore and offshore. Sea lions stun and feed on herring at the water surface, a behavior that also facilitates surface feeding by glaucous-winged gulls (Thomas and Thorne 2001, 2003). Disruption of herring schools by foraging humpback whales may also allow for increased sea lions and bird access to the fish (Rice et al. 2011).

The seasonal availability of herring is important to the fitness of many birds and shortage of food resources may affect both adults and chick survival (Kitaysky et al. 2000). For resident avian species, seasonal foraging on herring spawn may allow for replenishment of fat stores after overwintering. Migrants may replenish depleted fat stores upon arrival and prior to breeding, often before continuing a northward migration (Bishop and Green 1999; Sullivan et al. 2002). Spring conditioning and fattening rates of scoters in Puget Sound is correlated with herring spawn availability (Anderson et al. 2005). Scoters aggregate to consume spawn when available and, in Southeast Alaska, the number of scoters foraging on a single spawning site may exceed 75,000 (Anderson et al.2009). Some scoters may actively search for herring in the spring (Lok et al. 2008). From 2003 to 2006, 14 stopover sites in Southeast Alaska were found to be closely associated with herring spawning and assumed to be critical to scoter migration (Lok et al. 2011). A study during 1995-2002 in British Columbia found more than 5,500 harlequin ducks, representing 55 to 87% of the wintering harlequin populations, gathered for 2-3 week periods during the herring spawn at Hornby Island. For most of the ducks, travel to the spawning location was not an opportunistic use of available forage along a migratory pathway; rather, ducks arrived from other locations, some from more than 80 km away, to exploit a valuable, short-term resource. Less extensive herring spawn in some areas during certain years was thought to be the cause of shifting sizes and number of harlequin flocks (Rodway et al. 2003). A decrease in piscivorous birds in Prince William Sound, for example, was thought to be related to changes in forage fish abundance, including herring, possibly brought on by a climatic regime shift in the North Pacific and exacerbated by the 1989 *Exxon Valdez* oil spill (Agler et al. 1999). There is also evidence that successful reproduction in some seabirds may require a threshold biomass of prey that is 1 to 3 orders of magnitude greater than what is required to meet metabolic energy demands (Cury et al. 2011). Incorporating the management of avian predators into herring management, including the adoption of strategies such as time-area closures of spawning grounds, may be crucial to the maintenance of herring and bird species alike (Rodway et al. 2003; Anderson et al. 2009).

The abundance trends of the predominant avian species that prey upon herring in Southeast Alaska vary, although most trend data indicate stable or decreasing populations. Abundance of glaucous-winged gulls appears to be stable or increasing in different areas of Alaska, including Southeast. Common murre populations are stable overall in Alaska, although data specific to Southeast is not available. Pelagic cormorant abundance is stable or decreasing in different areas of Alaska, including Southeast (Dragoo et al. 2012). The number of marbled murrelets in Alaska has decreased significantly over the past few decades, which also includes declining trends in Southeast Alaska (Piatt et al. 2007). Although estimates specific to Southeast are not available, the population of surf scoters in Alaska also appears to be declining (SDJV 2008). Information on surfbird and mew gull population trends in Southeast Alaska is not available. While the interactions between herring and bird species that prey upon herring are complex, there is no evidence to suggest that avian predation on Pacific herring is currently increasing in Southeast Alaska.

6.3.1.3 Invertebrates and piscivorous fish

<u>Invertebrates</u>
All life stages of herring are subject to predation, by both vertebrates and invertebrates. Invertebrates may also be significant predators of herring. Consumption of herring eggs by epibenthic invertebrates off the coast of British Columbia averaged 3.7% of the total available eggs, and ranged from 1 to 30% depending upon the density of spawn and the abundance of predators. Predators were primarily crabs and, secondarily, sea anemones, but also included sea cucumbers, snails, sea stars, sea urchins, and chitons (Haegele 1993b). In another British Columbia spawning event, major predatory impacts were suggested by the ubiquitous presence of an estimated 9.4 million leather stars and 16.4 million turban snails over all the spawning grounds. It was further estimated that these invertebrates could consume 1,020 tons of herring over the 14 day incubation, more than either birds (271 tons) or gray whales (235 tons) (Haegele and Schweigert 1989).

Invertebrates may also target herring life stages other than spawn. Herring larvae are preyed upon by several species of hydromedusae in both British Columbia and Southeast Alaska coastal waters. For example, consumption by *Aequorea victoria* was estimated at 0.9 to 9.0% of the herring larvae during peak larval abundance (Arai and Hay 1982). Another study in British Columbia estimated consumption by *A. victoria* ranged from 4.4 to 95.8% of the herring larvae located in the surface 5 m. 14 – 21 days after the herring had spawned, possibly surpassing mortality from food limitation (Purcell and Grover 1990). Newly hatched herring larvae composed up to 48% of all prey ingested by *A. victoria* off British Columbia, and the potential effect on fish populations was considered widespread because this jellyfish species is found in temperate and subarctic waters throughout the Pacific (Purcell 1989).

Piscivorous Fishes

A variety of fish species may also function as major consumers of herring. Between 1977 and 1997, research showed that the consumption of Atlantic herring by 12 piscivorous fish species was probably large relative to standing stocks of herring. Herring were prominent prey, and consumption by the predatory fish appeared to track their abundance closely; for example, predation increased as the herring stock was rebuilding in the 1990's. Consumption during this period was greater than landings, and changes in predatory fish abundance had potentially important implications for long term fishery yields (Overholtz et al. 2000).

Several fish species in the North Pacific have been noted to prey upon herring. In Bering Sea surveys conducted between May and September from 1987 through 1989, Pacific cod, walleye pollock, arrowtooth flounder, and Pacific halibut were the primary species that preyed upon herring, with cod as the main predator. Groundfish predation was estimated at 5% of the available herring biomass in 1987, and 3% in 1988. Herring consumption by groundfish predators in the eastern Bering Sea was sporadic over time and space (i.e., no density dependent response), with the predation level possibly related to encounter rates with herring schools rather than the overall biomass. However, it was also speculated that herring constitute a larger fraction of the groundfish diet during autumn and winter when adult herring are more available (Livingston et al. 1993).

In Prince William Sound, surveys of fish preying on juvenile herring showed that Pacific cod were the most abundant predator, followed by great sculpin (Bishop and Powers 2010). Another study in Prince William Sound indicated two greenling species consumed between 2.3 and 3.7% of the total herring eggs deposited on Montague Island in 1995 (Rooper and Haldorson 2000).

In British Columbia and along the west coast, Pacific hake and Pacific cod were the principal predators of herring (Walters et al. 1986; Ware 1991; Ressler et al. 2007), although numerous other fish species were also considered to be important predators. The abundances of Pacific cod and herring in British Columbia were inversely related; the authors postulated that peak cod abundance during the late 1950s may have exacerbated the 1960's collapse of the herring reduction fishery (Walters et al. 1986). Other fish species off the west coast of Vancouver Island noted to prey upon herring include: lingcod, chinook and coho salmon, Pacific halibut, sablefish, and spiny dogfish (FOC 2010). Other herring predators along the coastal North Pacific include steelhead and sculpin (Fresh et al. 1981).

Most of the above piscivorous fish species are also abundant in Southeast Alaska and have been recognized as herring predators. A study assessing the summer food habits of predator species from a variety of Southeast Alaskan inshore, strait, and coastal epipelagic habitats, found that herring were present in the diet of 8 out of 18 predator species, including Chinook, coho, pink, and chum salmon, walleye pollock, sablefish, spiny dogfish, Pacific sandfish, with frequency of occurrences in the predator diet ranging from 0.2% in sablefish to 48.3% in Pacific sandfish (Sturdevant et al. 2012). However, estimating the frequency of predation on herring by a particular species is confounded by multiple life histories which may or may not overlap in space or time (Csepp et al. 2011). Quantifying the impact of piscivorous fish on herring biomass may be difficult due to a lack of knowledge concerning the biology and ecology of a particular species, including inter- and intra-specific dynamics. For example, while sablefish, halibut, Pacific cod, and lingcod are all herring predators, juvenile sablefish may also be consumed by halibut, cod and lingcod (Carroll and Brylinsky 2010).

Another difficulty in quantifying the effects of fish predation on the biomass of herring in Southeast Alaska is that some species are not of commercial importance and, therefore, population trajectories are not well defined. However, some general demographic information is available:

- Halibut biomass in southeast Alaska (Area 2C) has declined steadily from the mid-1990s (Hare 2010).

- No reliable estimates for lingcod biomass in Southeast Alaska are currently available, although the directed harvest (in round lbs) for lingcod in Southeast Alaska increased from a low of approximately 163,000 in 1987 to a high of 666,000 in 1995, and subsequently decreased to 270,000 in 2008. The total reported commercial harvest increased by 19% during 2005–2008 (Brylinsky et al. 2008).

- The abundance of sablefish in Southeast Alaska, as indicated by catch-per-unit-effort (CPUE), has fluctuated since 1997. The CPUE for the Southern Southeast Inside fishery generally increased from the 1980s to 2000s (Sayer and Holum 2008). In the Northern Southeast Inside fishery, no significant recruitment has been observed since 2000 and there are concerns that current stock levels are low compared to historic levels (Carroll and Brylinsky 2010).

- No standardized stock assessment surveys exist for Pacific cod in Southeast Alaska, although the reported harvest (in round lbs) increased from a low of approximately 133,000 lbs in 1985 to a high of 890,000 lbs. in 1993, and subsequently decreased to 461,000 lbs. in 2008 (Brylinsky et al. 2008).

- The abundance of arrowtooth flounder has increased over the last 40 years in both Southeast Alaska (Guenette et al. 2006) and the Gulf of Alaska (Turnock 2010).

- Pacific salmon species may also function as both predators and competitors of herring, with Chinook and coho being potential predators and pink, chum, and coho being potential competitors (Fresh et al. 1981; Purcell and Sturdevant 2001).

  Salmon production has increased over the last several decades, with hatchery fish accounting for a variable component of harvested salmon (Figs. 33, 34, and 35). In 2010, hatcheries in the Southeast Alaska enhancement program accounted for 18% of the total salmon in the common property commercial harvest, including 73% of the chum salmon, 22% of the Chinook salmon, 8% of the sockeye, 3% of the pink salmon and 28% of the coho salmon (Piston and Heinl 2011a; Piston and Heinl 2011b; White 2011).

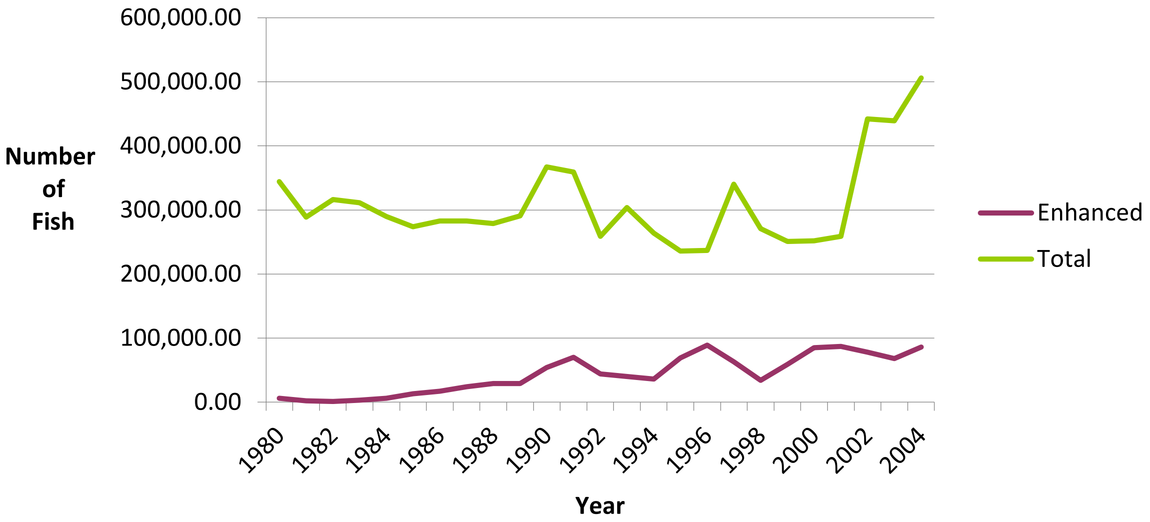


Figure 32. Chinook salmon total harvest and hatchery contribution (enhanced) in Southeast Alaska, 1980 – 2004 (Pryor et al. 2009).

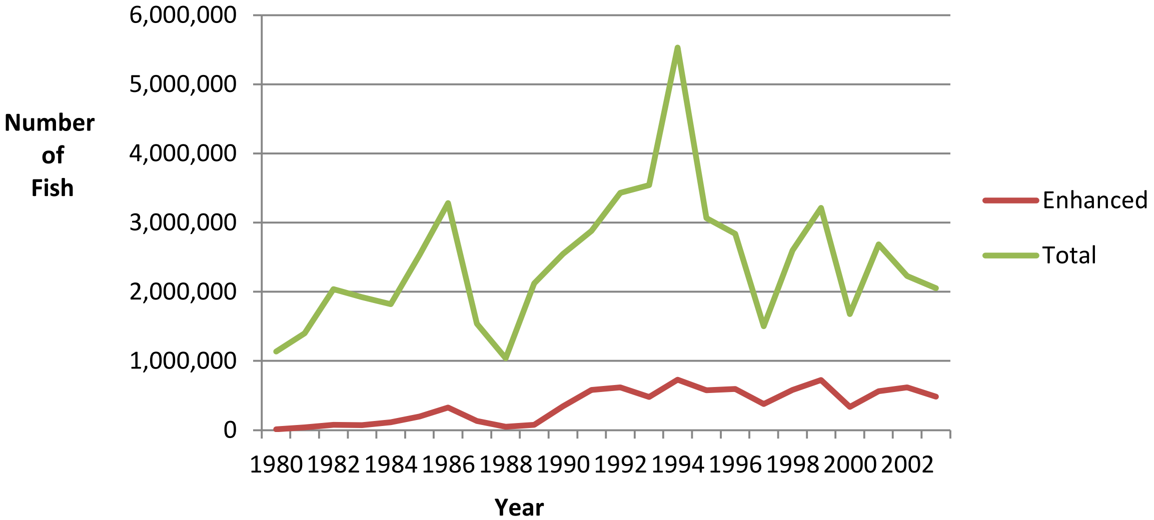


Figure 33. Total commercial coho salmon harvest with hatchery contribution (enhanced) in Southeast Alaska, 1980–2003 (Duckett et al. 2010).

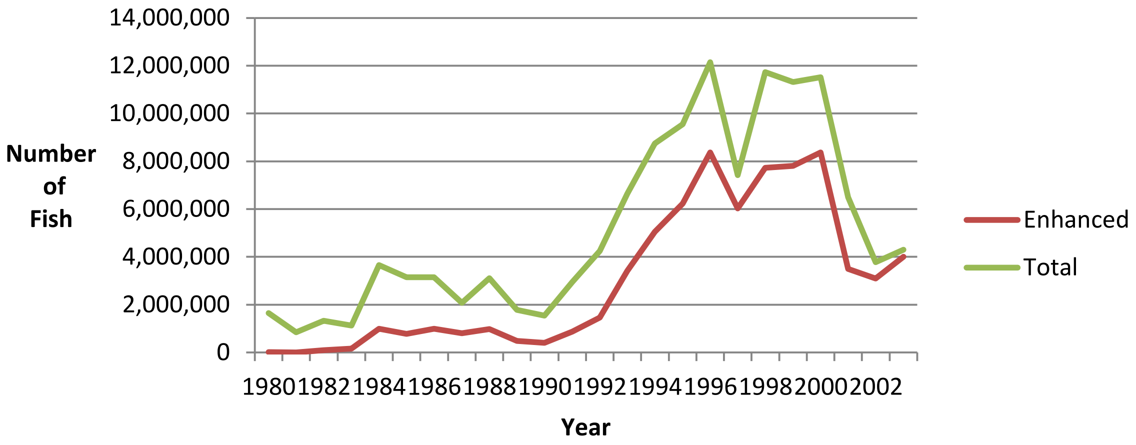


Figure 34. Total commercial chum salmon harvest with hatchery contribution (enhanced) in Southeast Alaska, 1980–2003 (Duckett et al. 2010).

The impact of salmon on herring in Southeast Alaska is not well understood. In 1959, the commercial utilization of a spawn-on-kelp fishery at Fish Egg Island near Craig was initiated amidst strong community protest based on the contention that “herring is the primary food of king salmon” and that depleting the herring stocks through the spawn fishery would adversely affect king salmon stocks (Rosier 1964). Since then, the ecological assessment of fish enhancement has mainly focused on potential interactions between wild and enhanced salmon, without significant consideration of impacts to predator or prey species (Bailey et al. 1975; Orsi et al. 2004; Duckett et al. 2010). While it has been suggested that salmon enhancement simply replaces, rather than augments, wild stocks, and the increase biomass of many salmon species is a consequence of optimum environmental conditions and not enhancement (Hilborn and Eggers 2000), impacts on some prey species may also be possible through the introduction of stocks in new locations. Enhanced salmon have been cultured and released from more than 20 hatcheries in Southeast Alaska; fish have also been imprinted and released from at least 150 additional remote sites (JRPT 2004). Although two of the standard practices in Southeast Alaska salmon enhancement include, (1) not releasing enhanced salmon close to significant wild stocks; and (2) building hatcheries in areas with minimal runs of wild stock, usually near an inlet or bay (Duckett et al. 2010), many hatcheries are either within, or close to, ADF&G herring stock boundaries (Fig. 36). Consequently, with newly recruited young-of-the-year herring abundant and aggregated in bays, herring may be the last prey that salmon encounter before entering their spawning streams (Stokesbury et al. 2002). Conversely, adult herring may also prey upon salmon fry in estuaries (Thorsteinsen 1965), and may be one of the largest consumers of pink salmon fry in Prince William Sound (PWS) each spring (Willette et al. 2001). Evidence in PWS further suggests that, at least for juvenile fish, competition may not be significant because juvenile pink salmon and age-0 herring exploit different portions of the annual production cycle with pink salmon targeting plankton species in the early spring and herring dependent upon summer and fall zooplankton (Cooney et al. 2001).

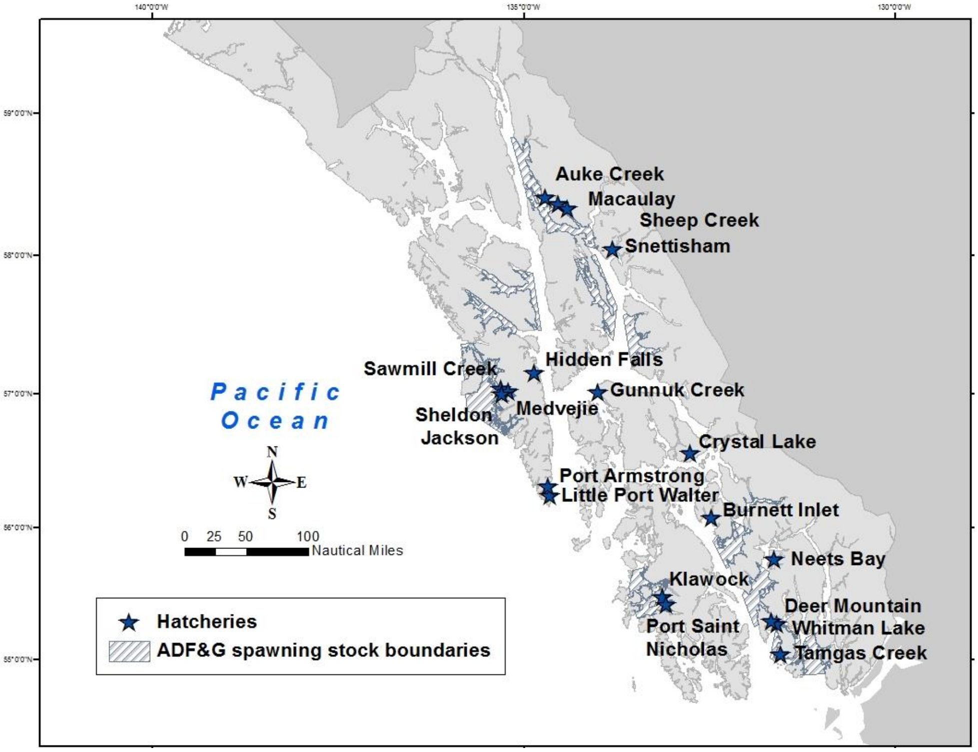


Figure 35. Location of salmon hatcheries (White 2011) in Southeast Alaska relative to ADF&G herring stock boundaries.

> In epipelagic habitat in Southeast Alaska, data collected from June to August/September between 1997 and 2010 showed a limited incidence of herring in adult salmon diets: pink 1.2% (n=420), chum 2.2% (n=91), coho 17.4% (n=115), sockeye 0.0% (n=20) and Chinook 5.5% (n=385). Adult coho were the most consistent predators on herring, with evidence of herring consumption in all but three years (Sturdevant et al. 2011). However, the availability of herring to these fish was unknown, and ascertaining the degree of salmon predation on herring may be confounded by many factors, including the possibility of opportunistic feeding, with salmon predation on herring varying between years, seasons, locations, and availability. In Southeast Alaska and northern BC, feeding habits of juvenile salmon were found to be dynamic, shifting among prey categories across salmon species, years, and areas (Landingham et al. 1998). Conversely, a broadscale comparison of juvenile salmon diets in North Pacific coastal marine waters indicated more variation between geographic regions than between time periods, although interspecific differences in diet were consistent regardless of the particular region or ecosystem. Consistent similarity of Chinook and coho salmon diets, for example, was largely based on high consumption of fish prey (Brodeur et al. 2007).

Finally, cannibalism has also been documented in both eastern and western populations of Atlantic herring (Fuiman 1989; Skaret et al. 2002) and also in Pacific herring (Hourston and Haegele 1980; Hourston et al. 1981). In Prince William Sound, age-1, -2 and- 3 juvenile herring decreased the probability of survival of eggs to age-1 juveniles, presumable through competition and cannibilism (Kiefer et al. 2010).

6.3.3 Summary

Many different species prey upon herring in Southeast Alaska, including marine mammals, birds, invertebrates and piscivorous fishes. These predator-prey relationships generally undergo persistent shifts and may be challenging to characterize on temporal or spatial scales. Furthermore, accurate trends in abundance are often not available for many bird, marine mammal and fish species known to prey upon herring. It is clear, however, that predation is a consistent source of mortality through all herring life stages and may be the primary source of mortality for some cohorts.

Two major marine mammal predators of herring, the humpback whale and Steller sea lion, are increasing in abundance in Southeast Alaska and it is uncertain if or when these species will reach their respective carrying capacities in the region. These marine mammal species may contribute significantly to the natural mortality of herring. Humpback whales in particular have been cited as potentially equivalent to a fishery in terms of herring biomass removal and have also been cited as causing delayed or suppressed recovery of some depleted herring stocks.

Although the interactions between herring and bird species that prey upon herring are complex, there is no evidence to suggest that avian predation is currently increasing as a threat to Southeast Alaska Pacific herring.

The extent or trends of invertebrate predation in Southeast Alaska has not been characterized. A multitude of piscivorous fish species may prey upon herring. Some of these species, such as halibut and sablefish, appear to be declining in Southeast Alaska while others, such as arrowtooth flounder and salmon, appear to have increased in abundance. The direct or indirect effects of these trends in abundance on herring biomass in Southeast Alaska is uncertain.

Both recruitment and adult population abundance of herring can be influenced by disease. Disease may significantly impact a stock or spawning group when the population is naïve and environmental factors promote disease manifestation as a co-factor with, or sequela to, other stressors. The chronic presence of disease may also prevent full recovery following a population decline. Although similar impacts may presumably occur on a metapopulation level when conditions are met, in Southeast Alaska disease epizootics have only been reported in specific stocks or localized areas. While disease may be a constant threat to herring stocks in Southeast Alaska, there is no evidence to indicate the presence of disease in itself as an increasing threat.

6.4 The Inadequacy of Existing Regulatory Mechanisms

6.4.1 Existing Regulatory Mechanisms

The Magnuson-Stevens Fishery Conservation and Management Act asserts federal authority over fishing in the Exclusive Economic Zone (EEZ), which in Alaska includes waters from three to 200 miles offshore of U.S. coasts. Waters within 3 miles of the coast are under state jurisdiction. Southeast Alaska herring are not managed within the EEZ; instead, the State of Alaska is the managing body for herring fisheries in Alaska (Woodby et al. 2005). Consequently, mechanisms in place that regulate human impacts on herring in Southeast Alaska are primarily in the form of mandates to state agencies based on state legislation. Article 8 Section 4 of the Alaskan

Constitution concerns the goal of sustainable yield, whereby “Fish…shall be utilized, developed and maintained on the sustained yield principle, subject to preferences among beneficial uses.” Regulatory mechanisms may include habitat protection or measures defining the limitations and extent of exploitation. Both may be inadequate if insufficient protection is offered against the risk of extinction.

6.4.1.1 Herring habitat

Discussion of herring habitat has generally focused on spawning grounds. However, while state regulations such as the Anadromous Fish Act and the Fishway Act were adopted to protect salmon spawning habitat, there are currently no state regulations that specifically protect herring spawning habitat in Alaska. Historically, ADF&G recommended in-water work timing windows for development projects under the Alaska Coastal Management Plan, which expired on July 1, 2011, and under the US Army Corps of Engineers (ACOE) project review process. Currently, ADF&G works directly with agencies requiring an authorization, such as ACOE or the Alaska Department of Natural Resources Mining, Land and Water, during project review and recommends measures to avoid, minimize, and mitigate impacts to herring (K. Kanouse, personal communication, 2/22/2012). The ADEC also implements Water Quality Standards which may indirectly affect herring habitat (ADF&G 2010a).

Discussion

In Southeast Alaska, there are currently no designated areas where encroachment or other human activities are permanently prohibited in order to protect herring spawning habitat. Habitat protection is limited to temporary avoidance/mitigation measures relative to spawning habitat, which may or may not offer sufficient protection. For example, the ACOE approved the installation of a permanent outfall pipe for a residential wastewater treatment plant in the intertidal zone of Sitka Sound spawning habitat. The temporary disturbance to spawning herring from in-water work of pipe placement was prohibited through the use of a timing window (no in-water work allowed from March 15 to May 15); however, the permanent impact of pipe and effluent on herring was not specifically addressed (ACOE 2012). Herring have been observed to alter primary spawning grounds in response to habitat impacts (Brown et al. 2002). Furthermore, new spawning grounds are not necessarily created as spawning grounds are lost. Consequently, the protection of existing spawning grounds, especially areas of repetitive events, may be paramount (Stephenson et al. 2001; Hay and Carter 2011).

6.4.1.2 Herring fisheries

Regulatory mechanisms with the greatest current impact on Southeast Alaska herring are ADF&G management plans and harvest strategies for exploited stocks. The Herring Management Plan for Southeast Alaska (5 AAC 27.190), adopted by the Alaska Board of Fisheries (BOF) in January 1994, regulates that the department (Pritchett 2008):

1. shall identify stocks of herring on a spawning area basis;
2. shall establish minimum spawning biomass thresholds below which fishing will not occur;
3. shall assess the abundance of mature herring for each stock before allowing fishing to occur;
4. except as provided elsewhere, may allow a harvest of herring at an exploitation rate between 10 and 20 percent of the estimated spawning biomass when that biomass is above the minimum threshold level;
5. may identify and consider sources of mortality in setting harvest guideline;

6. by emergency order, may modify fishing periods to minimize incidental mortalities during commercial fisheries.

Stock identification

For management purposes, herring stocks are currently synonymous with spawning aggregations. In the 1980's, stocks were defined as "concentrations of herring occupying the same distinct fishing ground during the fishing season over a succession of years," allowing the concentrations to be managed as fishing units (Blankenbeckler 1987). In 1994, the Herring Management Plan shifted harvest policy from targeting widely dispersed overwintering herring concentrations to management based strictly on spawning area populations. Fisheries are limited to the spawning populations with quotas based upon surveys from these areas (Davidson et al. 2011). Since then, ADF&G has conducted annual stock assessments in Southeast Alaska at the nine separate areas, including Sitka Sound, West Behm Canal, Seymour Canal, Hobart Bay/Port Houghton, Hoonah Sound, Ernest Sound, Tenakee Inlet, Revilla Channel, and Craig/Klawock (Fig. 37). In Lynn Canal, annual stock assessment surveys have been conducted since 2004.In any given year, it is probable that these sites collectively account for 95–98% of the spawning biomass in Southeast Alaska. Minor spawning occurs in other areas, but stock assessments at these locations are either not performed or limited to aerial surveys (Hebert and Dressel 2009). In recent years the department has documented herring spawn opportunistically at:

- Bradfield Canal (consistently observed spawn with large spawn events in recent years, spawn deposition surveys were conducted in 1 or 2 years)
- Pat's Creek (consistently observed with spawn events appearing to be growing)
- Back Channel (Mill Creek, Madden Bay area; consistently observed)
- Port Camden (we have observed spawn there fairly consistently or have had it reported to us by one the local air carriers)
- Pybus Bay (probably happens every year but not documented)
- Gambier Bay
- Farragut Bay (consistently observed spawn since it is on the way to Hobart)
- Bear Creek (SE Frederick Sound on Mitkof Island; spawn observed fairly consistently)
- Scow Bay (Scow Bay and in the north part of Wrangell Narrows, spawn deposition survey conducted 1 year)
- Duncan Canal
- Pillar and Rowan Bays
- Tebenkof Bay
- Lower Rocky Pass including Alvin and Reid Bays and Three Mile Arm
- Port Beuclerc
- Affleck Canal
- Burnett, Mosman and McHenry Inlets
- Ratz Harbor
- Olivers Inlet
- Port Frederick
- Taku Harbor
- Kasaan
- Annette Island (department routinely observes herring spawn activity on Annette as part of flying herring spawn in State waters)

- Lisianski
- Slocum (spawn deposition survey conducted 1 year)
- Mud Bay

The total mature spawning biomass for the areas above is not known but when opportunistically estimated (as was the case in Slocum Arm in 2012) can be substantial. (ADF&G 2013).

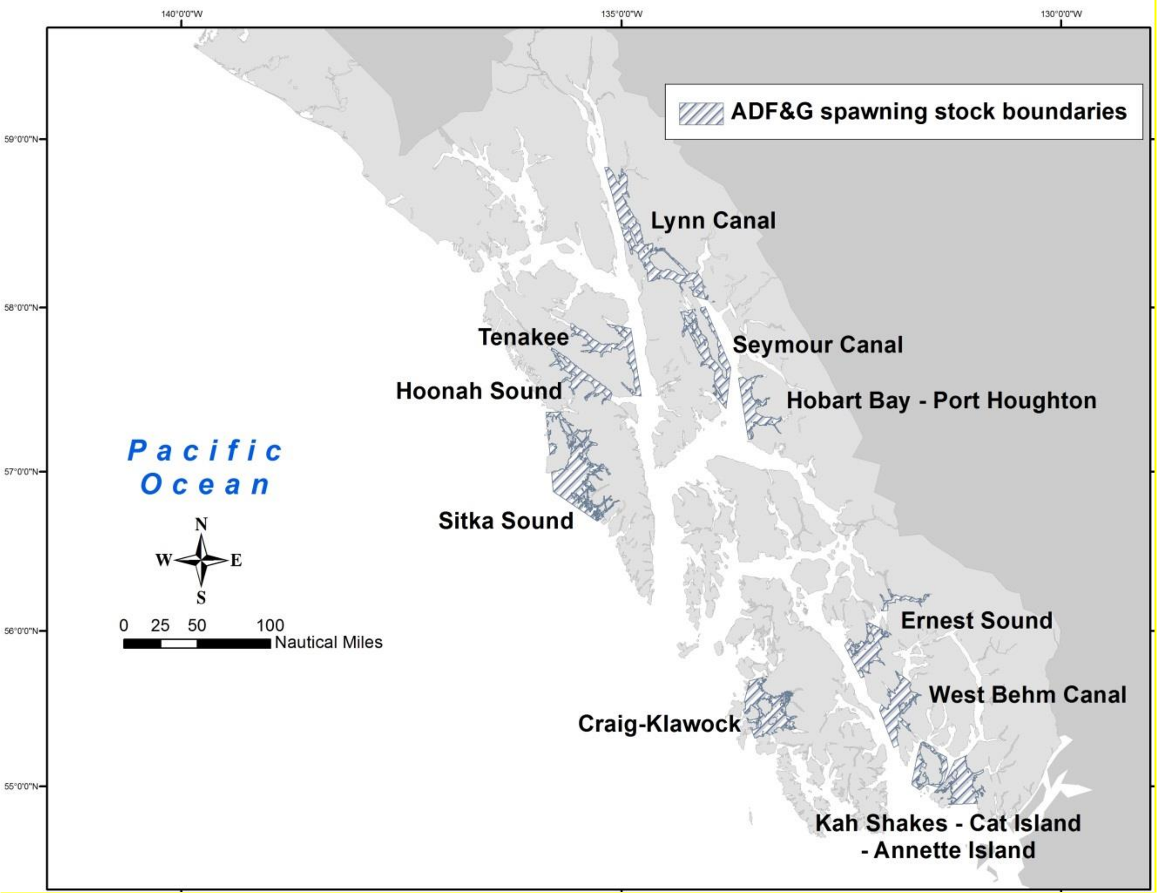


Figure 36. ADF&G Herring Stock Assessment Boundaries (Data courtesy of ADF&G).

Discussion

Understanding the dynamics of a population, including the extent of fish movements, is an essential goal for sustainable management (Wildes et al. 2011). However, understanding fish population dynamics for any marine species may be extremely challenging. As early as 1930, fluctuations in Southeast Alaska's herring abundance relative to migration and spawning areas were in question. The extent of herring schooling was considered to have a fundamental bearing on the depletion, fluctuation, and administration of the fishery. If migration was indiscriminate, for example, then overfishing in one area could result in a general depletion and all of southeast Alaska would require consideration as a management unit. On the other hand, if local "races" were present with limited migration, each locality could be treated as a separate unit since a reduction in one area would not affect the supply in another (Rounsefell 1930; Tester 1933).

ADF&G currently manages spawning stocks of herring in nine separate units. Although ADF&G considers some migration between stocks as probable, the percentage of fish intermingling is considered low but unknown (S. Dressel, personal communication, 1/26/ 2010). Therefore, the stocks are managed as closed systems without accounting for recruitment from other populations. However, the movement of herring among spawning grounds is not well understood.

In the North Sea, both climate and fisheries have triggered historical changes in migratory patterns of herring (Varpe et al. 2005). Petitgas (2006) hypothesized that spawning migrations are sustained by repeat spawners that lead first-time spawners to maintain the life cycle pattern. Research suggests shifts in migration patterns are usually initiated by a recruiting year-class starting its first migration but lacking “guidance” from older herring while encountering interannnual changes in environmental conditions (Corten 2002). Cohesion may exist among groups of similar origin, without a genetic basis, and aggregation and recognition of these “conspecifics” may endure for considerable periods, possibly for life (Hay and McKinnell 2002).

A density-dependent spawning ground selection, expanding when the population is large and contracting to the most suitable sites at smaller population sizes, appears to be a common trend in Pacific, Atlantic and Baltic herring (Ivshina 2001; Norcross and Brown 2001). It is possible that the expanding population of Sitka Sound herring, for example, may partly result from contracted spawning grounds elsewhere, although to date no research corroborates this speculation. The mechanisms initiating the return of herring to recolonize old spawning grounds is not well understood. The process may be stochastic or, alternatively, stem from factors intrinsic to herring or habitat. Along with many other animals, including reptiles (Stamps 1988) marine fishes (Lecchini et al. 2007) and invertebrates (Minchinton 1997; Donohue 2006), herring may exhibit “conspecific attraction”, which is the preferential settlement into patches of habitat with conspecifics. The health of a metapopulation is then partially described by the equilibrium between colonization and local extinction (Smith and Peacock 1990). Herring may disappear en masse from previous spawning grounds, with smaller aggregations having a higher probability of disappearance, and potentially reappear as a result of conspecific attraction or possibly when suitable conditions return to a vacant habitat (Ware and Tovey 2004). In Norwegian spring-spawning herring, fish may skip a second spawning migration due to the energetic cost under unfavorable climatic and herring body conditions (Engelhard and Heino 2006).

In British Columbia, straying rates among spawning areas were estimated at 4–25% annually with straying increasing linearly as populations approached carrying capacity and decreasing exponentially with distance between populations (Ware et al. 2000). Fidelity rates of herring stocks appeared to depend upon geographic scale, approaching 80 to 90% at an approximate area of 5000 to 10,000 km^2 with areas < 100 km^2 having almost no detectable fidelity (Hay et al. 2001). Herring are known to mix at feeding grounds in Southeast Alaska, but the extent of fidelity to both feeding grounds and specific spawning sites is uncertain (Carlson 1977; Carls et al. 2008).

Establishment of minimum spawning biomass thresholds

Regulations regarding allowable exploitation levels of Southeast Alaska herring have evolved through time. Early fisheries were largely unregulated, but a sharp decline in yield in 1938 was followed by the 1940 establishment of catch quotas which continued until 1966 when management was changed from the U.S. Bureau of Fisheries to the Alaska Department of Fish and Game (Reid 1971; K. Hebert, personal communication, ADF&G). Beginning in the 1970's, herring fisheries were managed as separate stocks on a quota basis, with 10–20% of the estimated biomass of each major stock harvested based on available data on total biomass, age, and growth. Beginning in 1978-79, no harvest was allowed on stocks of unknown size (Blankenbeckler and Larson 1982). Harvest rates in the 1980s were "set at a conservative level to build herring stocks to an overall higher level than the 1970's" (Blankenbeckler 1987). In 1983, ADF&G instituted, and continues to use, a threshold management strategy that allows harvest for each fishing area only if the spawning biomass forecast is above a predetermined threshold. A threshold may be defined as a "percentage of the long-term average of annual spawning biomass in the absence of fishing or average unfished biomass (AUB) under average environmental conditions." Zheng et al. (1993) conducted computer simulations to evaluate threshold management strategies in the Eastern Bering Sea and Prince William Sound, in which thresholds from 0 to 60% were examined with a variety of exploitation rates. It was determined that, at least for a single species model with an exploitation rate of 20%, a threshold of 25% AUB would likely be a safe approach for Alaskan herring. In British Columbia, the minimum level for herring stocks has been 25% of the AUB since 1985 (Schweigert et al. 2007).

Threshold management aims to balance conservation and utilization. In Southeast Alaska, threshold levels are intended to "protect herring stocks from sharp reductions in recruitment failure, to maintain adequate abundance of herring as prey for commercially important species such as salmon and to provide for the highest quality commercial herring products" (Carlile 1998a). Threshold biomass levels are also intended to maintain adequate herring abundance for predators (Hebert 2009).

Current thresholds for Southeast Alaska herring populations are (Prichett and Hebert 2008; Thynes et al. 2012):

Area	**Threshold Level (tons)**
Sitka Sound	25,000
Revilla Channel	6,000
West Behm Canal	6,000
Craig/Klawock	5,000
Seymour Canal	3,000
Tenakee Inlet	3,000
Ernest Sound'	2,500
Hobart Bay/Port Houghton	2,000
Hoonah Sound	1,000
Lynn Canal	5,000
Anita Bay	2,500
Port Camden	2,500
Lisianski Inlet	2,500
Tongass Narrows, George and Carroll Inlets	3,500
Other aggregates not included above	2,000

Herring aggregates of less than 2,000 tons are not considered for harvesting except for Hoonah spawn-on-kelp with a threshold of 1,000 tons (Pritchett and Hebert 2008). Based on data collected from 1970 to 1983, most stocks were assigned a threshold based on stock size, amount and quality of data, variability, stability or consistency of spawning, and fishery manageability (.e.g., the sac roe fishery with 48 permit holders require more intensive management). Initial assigned thresholds included 2000 tons for small stocks (e.g. Hobart Bay/Port Houghton), 2500 tons (e.g. Lisianski Inlet), 3000 tons (e.g. Seymour Canal) for medium stocks, 3500 tons (e.g. Tongass Narrows, George Inlet, Carroll Inlet combined), 5000 tons for large stocks (e.g. Juneau) and 7500 tons for Sitka (Blankenbeckler and Larson 1985). A quantitative method involving age-structured analysis (ASA) was used to reassess thresholds for Sitka and Tenakee in 1998 and for West Behm in 2003 (Carlile 1998a, 1998b; 2003). The ASA approach incorporates multiple data sources to provide the most probabilistic estimates of annual spawning abundance across the available time series.

Discussion

Successful recruitment is necessary to sustain a population and the spawning population must be of adequate size to provide sufficient reproductive output to support recruitment. To maintain spawning stocks above critical levels, ADF&G uses the concept of thresholds, whereby fishing does not occur if the estimated spawning stock is below a prescribed threshold biomass.

Successful application of thresholds requires accurate methods of estimation and evaluation of thresholds on fish population and yields (Quinn et al. 1990). A threshold that is too low offers insufficient protection against depletion. In ten vertebrate populations whose declines to extinction were monitored over 12 years, aspects of the populations dynamics deteriorated as extinction neared. Across populations, detrended variability in year-to-year rates of decline increased as extinction neared, underscoring the importance of characterizing critical population thresholds (Fagan and Holmes 2006), perhaps especially important for species such as herring with wide abundance fluctuations. However, it is difficult to distinguish between a “conservation threshold,” below which reproductive failure and extinction may occur, and a “productivity threshold,” below which a reduced population may quickly rebuild to commercially productive levels (Funk and Rowell 1995).

One of the main variables in establishing a threshold includes the determination of the AUB or “pristine biomass”. The accuracy of estimating the AUB depends upon population estimates; however, the AUB is most often based on historical data collected under the influence of fishing (Funk and Rowell 1995; Hseih et al. 2006). True AUB will have occurred before abundance data were collected and, for most fish populations including herring, reliable data have only been available for the past two to four decades (Hutchings and Reynolds 2004). The current biomass of many fish populations, including spawning stocks of both Atlantic and Pacific herring, is estimated to have been reduced by many orders of magnitude from levels prior to industrialized fishing (Beverton 1990; Jackson et al. 2001; MEA 2005). If a stock is only a small fraction of the biomass before industrialized fishing, the concept of sustainability upon which most quantitative fisheries management is based comes into question (Pauly et al. 2002), including the concept of AUB.

In Southeast Alaska, historical harvesting of both herring, whales and other marine species (as potentially significant predators and competitors) since the early 1900’s, as well as uncharacterized regime shifts that may have occurred, make it likely that population structures and trophic linkages in the underlying ecosystem have changed significantly since commercial fishing truly began making the characterization of AUB challenging. In other cases, initial thresholds were based on: 1. historic estimates of abundance; 2. historical and personal knowledge; 3. biologists' judgement regarding minimum quotas that could be managed and controlled (Carlile 2003). Consequently, methods used to establish thresholds, including the adoption of reference points that stem from an estimated AUB, are most likely examples of a "shifting baseline syndrome," whereby more recent data is accepted as a baseline to substitute for a much different baseline that occurred before humans began having major impacts, potentially leading to inappropriate reference points (Pauly 1995). In order to allow modifications for conservation and development purposes based upon new information, ADF&G did exclude quantified threshold levels from the management plan (ADF&G 2012f), and some of the thresholds have since been modified.

In 1983, for example, the herring population in the Juneau Area, from Auke Bay to Berners Bay, declined rapidly. The threshold was increased to 10 million pounds (5,000 tons) after it was determined that the current threshold of 8 million pounds had not sufficiently protected the stock against successive year class failures. A 1985 ADF&G memo stated that "it is evident the past threshold level did not adequately guard against the failure of many successive year class failures and the subsequent critical low level of the present population….The present extreme low herring population level in the Juneau area will make it difficult for the population to return to normal levels without extremely strong recruitment. The chance of this happening to a degree that will restore the population to a normal size in the near future is very small" (ADF&G 1985).

In 2003, the threshold for West Behm Canal was tripled from 2,000 tons to 6,000 following an analysis to estimate 25% of AUB, which was done in preparation for consideration of a proposal before the Board of Fisheries that would allow a commercial fishery on that stock. The intent was to provide the BOF a realistic threshold that would protect the stock while the proposal was under consideration. However, models used to determine this threshold were based on only 9 years of data in which sampling was initiated after an observed increase in spawning activity. The short time series for population parameters, the lack of inclusive data when spawning was low, and the lack of an established spawner/recruit relationship introduce added uncertainty into the population model and threshold analysis (Carlile 2003); it was for these reasons that a threshold greater than the most conservative of model scenario results was implemented.

Threshold management, while aiming to conserve fish stocks and minimize the risk of collapse, is also determined by trade-offs among benefits and costs. Because a closed fishery impacts economics, threshold levels may be also adjusted according to social and political circumstance. In Sitka Sound, the initial threshold was set at 6,000 tons in 1977 and changed to 7,500 tons in 1982 based upon an increase in population size (ADF&G 2012f). In 1997, ASA modeling was used to recalculate the threshold, and based on 25% of AUB, increased to 16,800 tons (Carlile 1998a) with a buffer added up to 20,000 tons (ADF&G 2000; K. Hebert, personal communication, ADF&G). In 2009, in order to provide more of a buffer for subsistence concerns, the threshold was further increased to 25,000 tons (K. Hebert, personal communication, 11/17/2010; Thynes 2010), over three times the initial threshold level.

Assessment of abundance

A variety of methods to assess herring biomass have also evolved through time. Before 1970, vessel-based visual estimates with depth sounders or sonar were conducted immediately prior to spawning or on winter aggregations as well as aerial or marine surveys of miles of spawn. A computer assisted hydroacoustic technique was used extensively between the late 1970's and the mid-1980s. Since 1976, starting with the Kah Shakes and Sitka stocks, spawn deposition surveys were adopted and remain the cornerstone of biomass assessment (Bergmann et al. 2009).

Spawn deposition surveys involve an aerial or skiff-based determination of the miles of beach containing spawn, as well as diver estimates of egg density. Regarding the latter, two person SCUBA teams perform visual estimates of egg density along a random series of transects with diver-specific correction factors later applied to the estimates. A 10% pre-survey egg loss correction factor is also added to the estimate to account for predation and wave-induced loss. Together, the information provides the total number of eggs in a survey area. Only aerial surveys are currently conducted on Revilla Channel spawning aggregations; if the spawning biomass is deemed sufficient, then further data is collected.

Other data is also collected to estimate for each stock average weight at age, average length at age, age composition of the spawning biomass, age composition of the commercial catch, and fecundity. This collected information is then incorporated into one of two analytical methods to forecast abundance with the end result being an estimate of the current year's abundance of mature (age 3+) herring and to forecast the abundance of herring for the following year (Carlile 1996; Pritchett 2007). These methods include: (1) biomass accounting (BA); and (2) ASA for herring stocks with longer time series of data. Though both methods use spawn deposition data acquired through surveys, the methods differ in the amount and type of data needed for the analysis.

- The BA model was first applied in 1995 and is currently used for Hobart Bay, Hoonah Sound, West Behm Canal, and Ernest Sound, stocks with shorter time series of data. The observed spawning biomass and age composition from one year is modified by annual growth and mortality estimates to produce the next year's abundance forecast (Hebert 2009). This method uses spawn deposition estimates of eggs, age composition of spawners, weight-at-age, fecundity, survival- and maturity-at–age, and median historical level of recruitment to forecast biomass (Bergmann et al. 2009)

- The ASA model uses a time series of total fishery catch, fishery and spawning population age compositions, fishery and spawning population weights-at-age, fecundity and spawn deposition data to estimate biomass. Besides the abundance time series, the model estimates survival, age-specific maturity, and gear selectivity. The product of natural mortality, age-specific maturity, and the current year's abundance are used to forecast the age-specific abundance of age 4+ herring in the subsequent year (Carlile 1996). The ASA method has been used to estimate populations in Craig, Sitka Sound, and Seymour Canal since 1993 and for Tenakee Inlet beginning in 2000 (Hebert 2009).

In 2008, ADF&G also incorporated annual variance estimates for the spawn deposition data, based on bootstrap methodology, into the Sitka Sound ASA model to indicate the amount of uncertainty in the population index data input. Thus, a year with high variance in the spawn deposition data is given less weight in the model. For example, the 2008 spawn deposition estimate for Sitka Sound was nearly three times larger than the 2007 estimate but had a higher variance; therefore, the 2008 spawn deposition data exerted less influence on the 2009 forecast (Thynes 2010).

Guidelines harvest levels resulting from ASA forecasts may be adjusted conservatively according to current conditions, including biomass adjustments to account for effects of potential changes in climate and mortality. Preliminary assessment for Sitka Sound in 2008 predicted a spawning biomass of 78,446 tons with a maximum GHL of 15,689 tons. Due to herring growth, maturation, and survival concerns, a more conservative GHL of 13, 796 tons was adopted and later changed to 14,723 tons following analysis of size-at-age data (Bergmann 2008). The phases of the Pacific Decadal Oscillation (PDO) index has also been used to define time periods for parameters estimated (Thynes et al. 2010).

Discussion

A stock assessment is the collection and analysis of demographic information about fish populations to provide an informed description of the status of a fish stock. Stock assessments incorporate various data sources, particularly those from fisheries and surveys. These source data, evaluated and weighted for informative value with statistical techniques, are then used to estimate abundance and population trends and potentially forecast future, near term population levels (National Resource Council 1998; Quinn and Deriso 1999; NMFS 2009a).

Accurate stock assessment is essential for the sustainability of commercially utilized species. Inaccuracies and uncertainties in the assessment process may arise from many sources, including: (1) an imperfect understanding of the drivers of ecosystem function affecting a species behavior, growth, and reproduction; (2) uncertainty about a species-biology, including growth rates, recruitment, movement patterns, and behavior; (3) sampling errors resulting in misrepresentation of stock and other empirical data; and (4) misspecification of predictive models arising from incomplete knowledge as well as from the practical limitations involved in mathematical expressions of biological processes (Rosenberg and Restrepo 1994; Nevill 2009). In British Columbia, eight of the nine major herring stocks sharply declined between 1963 and 1967. Causes cited for the declines included poor recruitment, increased fishing mortality, and the inability of stock assessments to detect downward trends in spawning biomass until the stocks were well into decline (Hourston 1980). In Lynn Canal an overestimation of the biomass by winter hydroacoustic surveys may have indirectly contributed to the stock collapse (Carls et al. 2008).

The methods of biomass assessment have changed over time. In Ernest Sound, for example, assessments were based on hydroacoustic surveys from 1971/72 through 1984/85, aerial surveys from 1985/86 through 1991/92, spawn deposition estimates from 1992/93 through 1994/95 and biomass accounting from 1995/96 through 2006/07 (Breese et al. 2012).

ADF&G uses data from previous years and mathematical modeling in a stock assessment to predict the following year’s return of spawning herring. At times, the forecast may deviate from the actual return (or hindcast estimate). Most often, ADF&G hindcast estimates are larger than forecasts, which offer an added measure of protection from overutilization. Occasionally, and often for unknown reasons, the hindcast estimate is substantially lower than the forecast estimate. The 2004 forecast for West Behm Canal, for example, was 9,366 tons or 3,000 tons above the threshold whereas the returning spawning biomass in 2005 was estimated to be 443 tons, less than half of the harvest limit (Thynes et al. 2010). In 2012, the harvest limit in Sitka Sound was set at 28,829 tons based on a forecast of 144,143 tons, but for unknown reasons the return was substantially less and the fishing discontinued at 13,534 tons (ADF&G 2012g; ADF&G 2012h).

Measurement error is the error in observed quantities such as the catch or average size-at-age (Rosenberg and Restrepo 1994). In late 2010, ADF&G discovered inconsistencies in the department's scale aging method for the period 1999–2010, which brought into question the reliability of age estimates during that period, as well as data used for age compositions, weight-at-age, spawn deposition biomass estimates, and all ASA model results including estimates of biomass, recruitment, survival and maturity (ADF&G 2010c; Thynes et al. 2012). This aging error was subsequently corrected after an enormous re-aging effort. Ultimately, although estimates of survival and maturity differed ASA biomass estimates were similar when using corrected or uncorrected aging.

Exploitation rate

Once spawning biomass estimates are calculated, they are compared to the threshold levels established for each stock. If the projected herring biomass exceeds the threshold, an established exploitation rate is applied to the excess and a guideline harvest level (GHL) determined for each region, which are then allocated to different fisheries. GHLs may be defined as "…the preseason estimated level of allowable fish harvest which will not jeopardize the sustained yield of the fish stocks" [5 AAC 39.975 (27)]. In Southeast Alaska, the GHL is established at 10–20% of the forecasted spawning stock with harvest limits changing relative to the population increase. When the spawning biomass is at or above the threshold level, the maximum harvest rate for all stocks except for Sitka Sound is 10%, plus an additional 2% for each incremental increase of spawning biomass equal to the threshold limit. (Thynes 2010). This stepped scale calculation used to determine the percent harvest rate is:

$$Maximum\ Harvest\ Rate = 8 + 2\left[\frac{Forecast\ Spawning\ Population}{Threshold\ Level}\right]$$

In 1997, the BOF adopted a different harvest rate for the Sitka Sound sac roe fishery:

$$Maximum\ Harvest\ Rate = 2 + 8\left[\frac{Forecast\ Spawning\ Population}{20{,}000}\right]$$

(Pritchett and Hebert 2008).

The difference between the two harvest rate equations essentially determines how quickly the maximum harvest rate of 20% will be reached relative to the estimated biomass. For all other stocks, the maximum harvest rate is capped at 20% when the biomass is six times the threshold. For the Sitka stock, the maximum harvest rate is capped at 20% when the biomass is a little over twice the threshold. The minimum harvest rate in Sitka also differs at 12%, which was set by the BOF in 2009 (Thynes et al. 2010).

Discussion
The GHL serves to inform the fishing industry of potential harvest availability and opportunity and as a guideline for in-season management objectives. ADF&G management staff may adaptively alter a GHL based on pre-fishery, on-the-grounds, biomass observations. In recent years, fishery implementation has been contingent on a preseason determination (often through acoustic or aerial surveys) that a herring biomass near or exceeding the preseason forecast is present.

There are no explicit regulatory consequences if the GHL for a given spawning population is exceeded in a given year; overages or underages are not applied to the following year. Instead, the biological consequences of either exceeding or coming in below GHLs are monitored during annual spawn deposition surveys and subsequent stock assessment. An area, district, section or portion thereof may close to fishing before or after the GHL has been reached if principles of management and conservation dictate such action (S. Dressel, personal communication, 5/2/2012). For example, in 1999 a GHL of 870 tons was established for the Kah Shakes stock, but due to on ground concerns over a lack of herring in State waters no herring were harvested (ADF&G 2000).

The Herring Management Plan for Southeast Alaska calls for a harvest rate of between 10 and 20%. Catch rates over or under the GHL result in exploitation rates above the 20% limit or below the 10% limit. The estimated exploitation rate calculated after the fishing season is over depends upon whether the forecast or hindcast of herring population biomass is used. For many stocks, a quantifiable volume of fish is harvested and then dive surveys estimate the remainder. These two quantities are added to create a hindcast estimate. If the ASA model is used on a stock, age composition, age at weight etc. data are combined with the survey estimate of egg abundance to calculate an ASA hindcast estimate which is considered more comprehensive than a survey hindcast estimate of biomass alone. BA and ASA models are also used to forecast population biomass the following year and it is this forecast upon which the GHL is based. Hindcast estimates are generally larger than the forecast estimates, which suggests that exploitation rates have been lower than target harvest rates and GHL's have often been set too low. Consequently, when the hindcast estimates are used, the exploitation rate exceeds the 20% much less frequently and then only when the hindcast estimates are less than the forecast estimates and the GHLs consequently set too high.

It is also possible that the GHL is met or exceeded prior to the "ground truthing" that occurs on the spawning grounds. For example, during the 1999/2000 season, the entire GHL of Port Houghton/ Hobart Bay was harvested in the winter bait fishery. The forecast was 3600 tons with a GHL of 418 tons. The WBF catch was 432 tons (ADF&G 2000a). With the commencement of spawning, the hindcast estimate was 1293 tons (ADF&G 2012), substantially lower than the forecast, and as a result the catch was about 36% of the biomass.

Modeling and mortality

Mortality is a measure of all factors that reduce the abundance of a closed population, including mortality from fishing and all other sources throughout the life history such as predation, disease and starvation. Most fishery models treat total mortality as an instantaneous rate, Z, where $Z = F + M$ with F as the fishing mortality rate and M as the natural mortality rate. This allows F, a primary focus of fishery management, to be considered separately from other sources of mortality.

The natural mortality rate, *M*, includes mortality from all non-fishing sources. Because most dead fish disappear without a trace, natural mortality is generally estimated indirectly through modeling rather than through direct biological observation (Tanasichuk 2000; Cotter 2004). The main methods used to estimate *M* are: (1) analysis of catch data; (2) correlation of *M* with other life history characteristics; and (3) estimation of deaths through predation (Vetter 1988). Most mathematical models of fish stock dynamics treat *M* as either a constant or an estimated parameter.

The analysis of catch data to estimate natural mortality involves tracking either relative or absolute abundance in groups of fish across two or more successive time periods (Vetter 1988). ADF&G uses ASA modeling to estimate natural survival (1 – natural mortality) over one or more time periods for which age-specific data on herring abundance are available. A separate estimate of natural survival is made for the Sitka, Craig, Seymour, and Tenakee spawning populations where ASA modeling is used. For each spawning population, one or more natural survival parameters are estimated, where a single parameter applies to a multi-year period and a number of multi-year periods may exist in the modeled time-series. The survival/mortality value may be adjusted or renewed according to trends that occur over blocks of time with indices, such as the PDO, used to modify survival estimates. Survival parameters estimated in ASA models from historical data are then used for forecasting biomasses for the following year. For stocks where ASA modeling is not used, a survival parameter is borrowed from the nearest or most similar ASA stock and is used to forecast biomass for the following year (S.Dressel, personal communication, 12/15/2010). In Sitka Sound herring, survival estimates changed from 57% during 1980–1998 to 79% in 1999–2011. In Seymour Canal, survival estimates shifted from 57% during 1980-1998 to 84% in 1999 to 2002 to 57% from 2003 to 2011. Craig survival estimates increased from 41% in 1988 to 1998 to 53% from 1999 to 2011(Data courtesy of ADF&G, 2012). The ADF&G model does not apportion predation and disease as separate components of natural mortality nor does it forecast upcoming conditions. Managers must assess field conditions, recognize potential catastrophic stock changes as they occur, and modify limits accordingly.

Discussion

Estimation error is the inaccuracy and imprecision in the estimated model parameters such as stock abundance or fishing mortality rate. (Rosenberg and Restrepo 1994). For Pacific herring in Alaska, population biomass has been modeled since the 1970s (Quinn et al 2001). Models to estimate fish populations commonly integrate many variables, including age, length, sex, fishing mortality, and indices of abundance. Uncertainty in modeling arises from inherent limitations in expressing biological processes in mathematical form, including an insufficiency of data, and also in the error associated with model parameters. In performing a science-based review of herring stock assessment and management framework following major stock declines, the Department of Fisheries and Oceans Canada compared different age-structured models for herring, including the model currently used. Although performance varied among models, no model provided a perfect fit and model output could differ substantially, e.g., over a 7-fold difference in estimated spawning biomass among models (Fu et al. 2004).

The accuracy of how models describe the herring stock depends upon what parameters are included in the model and how the datasets are weighted. One of the most difficult parameters to estimate in fishery models is natural mortality, or M (Hoenig 2005; Shertzer et al. 2008). While M is often treated as a constant, current evidence suggests that M is not constant, either within a single stock over time or among stocks of a given species in different areas. Furthermore, the effect of M in defining biomass can considerable, depending upon the values chosen for other parameters, and the form chosen for the estimate(s) of M. For example, when post-fishery spawning biomass in the Eastern Bering Sea was compared using M values of 0.30 and 0.39, mean biomass values differed substantially: 391,090 versus 235,925 t at a 10% exploitation rate and 53,810 versus 19, 398 t at 40% exploitation (Fried and Wespestad 1985).

Many factors will influence the magnitude of M, including age, density, disease, parasite load, food supply, predator abundance, water temperature, sex, and size (Vetter 1988). Age, for example, can lead to substantial variation in M. Although estimates of age-specific natural mortality are surrounded by a high degree of uncertainty (Hollowed et al. 2000), natural mortality in herring is generally considered highest during egg and larval stages, with a progressive decrease as herring grow older (Stokesbury et al. 2002), followed by a potential increase with senescence (Skud 1963;Tanasichuk 2000). Natural mortality also varies interannually (Hollowed et al. 2000; Moustahfid et al. 2009). In Prince William Sound, for example, estimates of M for both young-of-the-year and one year old herring doubled between 1996 and 1997 for both groups (Stokesbury et al. 2002).

Although direct evidence is lacking, predation is probably the most important factor affecting M (Haist et al. 1993). When comparing constant vs. density-dependent M through a separable sequential population model for British Columbia herring stocks, model fit improved substantially by increasing M at low stock abundances, supporting the theory that predators consume a greater proportion of the stock as biomass decreases (Haist et al. 1993). In modeling trophic relationships of nine important fish species on Georges Bank from 1978 to 1992, including six predators and herring as an important prey species, predation mortality caused by the six predators was found to be high compared with residual natural mortality. Predation was considered an important source of mortality in Georges Bank with considerable impacts on prey species. Recommendations included incorporating future predator abundance into recruitment projections for prey species that suffer high pre-recruit predation, including herring (Tsou and Collie, 2001). Models not accounting specifically for predation tend to underestimate uncertainty (Vetter 1988; Mousthafid et al. 2009), and biological reference points also differ considerably (Hollowed et al. 2000; Overholtz et al. 2008; Tyrell et al. 2008; Moustahfid et al. 2009). When a fishery and predators both remove significant amounts of biomass, the result can be heightened potential for prey stock decline (Overholtz et al. 2000) and longer recovery time. The Gulf of Maine Atlantic herring stock collapse in the 1970s may have occurred because simultaneous removals of large portions of the biomass by predators and the fishery was not sustainable. Conversely, incorporation of poorly estimated predation may result in model misspecification or over-parameterization.

The importance of modeling the components of natural mortality and incorporating ecosystem aspects into traditional stock assessment models was further suggested in a study that described the impacts of minke whale predation on Norwegian spring-spawning herring. Although the abundance of both populations changed over time and space, a strong predator/prey relationship existed such that including minke whale predation into herring stock assessment models was recommended (Tjelmeland and Lindstrom 2005). Accounting for shifts in species composition, size structure, and the distribution of predator biomass are important considerations for ecosystem-based fisheries management (Tyrell et al. 2008). In Prince William Sound, including humpback whale abundance trends improved ASA model fit. Results suggest the impact of humpback whales on herring in Prince William Sound is comparable to disease or fishing in magnitude (Teerlink and Quinn *in prep*.).

The same may be true for disease in a population. The presence of disease may strongly affect recruitment and adult population abundance. Therefore, modeling specifically for disease prevalence may improve the accuracy of biomass estimates (Patterson 1996; Quinn et al. 2001; Marty et al. 2003). Because population models provide the basis for establishing commercial harvest quotas, errors in model estimates can also put a diseased population at risk of overharvest. For Prince William Sound herring in 1999, the traditional model estimated a biomass above the harvest threshold. When disease information was added, the model more accurately predicted a biomass below threshold values and the fishery was closed (Marty et al. 2003). Furthermore, in 1993 and from 1997 through 1998, a higher VHSV prevalence in Prince William Sound resulted in a higher natural mortality and a reduced estimate of spawning biomass. It was concluded that ongoing collection of disease information is necessary for accurate forecasting and careful management and that a conservative assessment policy should use a disease model and refine it as new data are available (Quinn et al. 2001). In all years from 1993 to 2006, the natural mortality of Prince William Sound herring was significantly greater than the assumed background mortality of 0.25 due to epizootics cycling through the adult population every four years. Despite low recruitment after 1992, the population may have recovered if it were not for disease (Marty et al. 2010).

ADF&G does not use a constant M in ASA modeling; rather, survival estimates may be adjusted or renewed according to trends that occur over blocks of time. The ASA model in Southeast Alaska does not apportion predation and disease as separate components of natural mortality nor does it forecast upcoming conditions. However, different M values are estimated by stock, which allows for time dependent parameterization of M within each ASA-modeled stock. These multiple estimates of M within a single stock over time can account for changes in natural mortality due to climate change, predation, or disease. While SE Alaska ASA models do not directly incorporate disease estimates like Prince William Sound models, ASA models used for Southeast Alaska herring estimate natural mortality and allow it to change over time, whereas Prince William Sound models assume an overall natural mortality that is partitioned with the disease index. Both allow the model to vary due to disease, but do so in different ways (ADF&G 2013).

Modify fishing periods by emergency order

Although ADF&G supports and receives direction from the BOF, the department is unique relative to many resource management agencies by virtue of being delegated Emergency Order authority which allows fishery managers to expeditiously open and close fisheries in response to in-season conditions.

6.4.1.3 Creation and adoption of regulations regarding herring fisheries

While the Southeast Alaska herring fishery is managed principally by ADF&G, fishery regulations are adopted by the BOF. The BOF was originally created by the state legislature to provide for an open public process and to give direction to ADF&G. The Board consists of seven members serving three-year terms. Members are appointed by the governor and confirmed by the legislature. Members are not required to be scientists or have a background in science to serve on the Board (ADF&G 2012f) .The main role of the BOF is to conserve and develop the fishery resources of the state, which involves setting seasons, bag limits, and methods and means for the state's subsistence, commercial, recreational, and personal use fisheries. The BOF is involved in setting policy and direction for the management of the state's fishery resources through development of fishery management plans and regulations, resource allocation among users. The ADF&G uses fisheries monitoring and research programs to document catches in season, assess stock condition, and determine appropriate harvest levels within BOF guidelines.

The BOF meets four to six times per year in communities around the state to consider proposed changes to fisheries regulations. The board uses the biological and socioeconomic information provided by the Alaska Department of Fish and Game, public comment received from people inside and outside of the state, and guidance from the Alaska Department of Public Safety and Alaska Department of Law when creating regulations (ADF&G 2012a,b).

The regulatory process is summarized in Figure 38. Written proposals, comments and oral testimony are submitted to the BOF from the public, ADF&G, and advisory committees (local "grass roots" groups that meet to discuss fishing and wildlife issues and to provide BOF input). Proposals from each major region are typically considered once every three years. The BOF then deliberates on these proposals and decisions are reached by majority vote. A legal review follows and the decisions are then made official by the Lieutenant Governor (ADF&G 2010a, b).

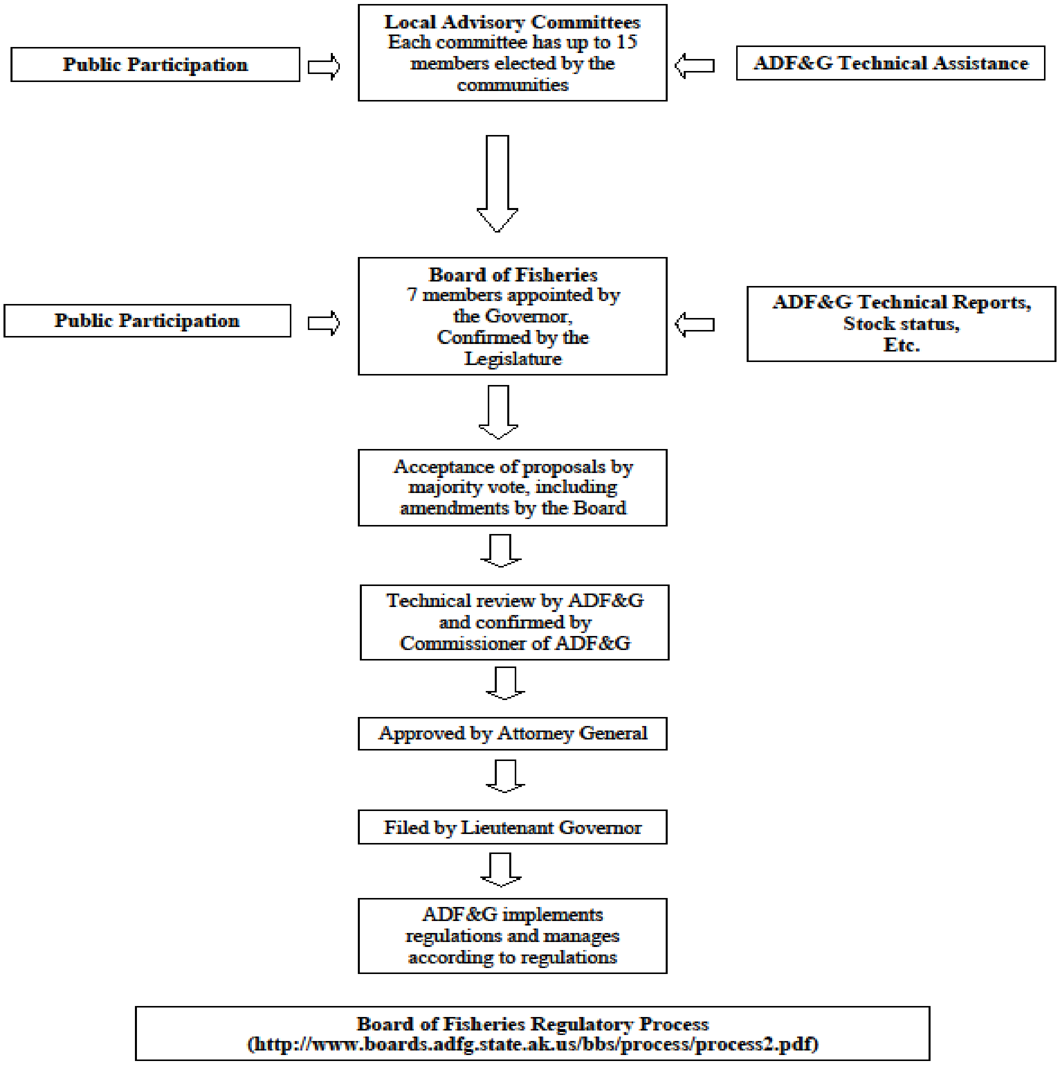


Figure 37. Southeast Alaska herring regulatory process (ADF&G 2010a).

Approximately 21 regulatory proposals were submitted to the BOF for the Southeast Alaska and Yakutat finfish meeting in 2012. Proposals included gear modifications, GHL reallocation and amendments, changes in thresholds, and measures to decrease the intensity of the competitive fishery in Sitka Sound (ADF&G 2012c).

Discussion

Throughout fishery management, a major source of uncertainty may result from non -science based influences on decision-making, with the weakest component of fishery management sometimes attributed to governance and not science (Browman and Stergiou 2004; Nevill 2009).However, non-science based management is less likely to ensure sustainability compared to science-based management. When a comparison was made of the scientific advice, management actions, and subsequent population trends of North Sea herring during two similar periods of significant stock depletion, the most successful and sustained recovery occurred with: (1) credible science; (2) a management system capable of making consistent decisions; (3) stakeholder willingness to accept management action; and (4) sustained recruitment. The primary conclusion was that sound scientific advice played a critical role in successfully confronting difficult management decisions and conducting good science was a necessary prerequisite (Simmonds 2007).

However, scientific advice may be downplayed in the hands of non-scientists who are, in many cases, responsible for creating or enforcing management plans (Mace and Hudson 1999). Elected officials respond to their constituencies and people most affected by fishing limits, and most involved, are the fishing industry. Consequently, commercial pressures may exert significant influence on resource managers to behave in a risk-prone way (Mace and Hudson 1999).

Guiding policies may also exploit resources until a problem occurs rather than adopting a precautionary approach. With respect to fishing regulations, management may be quicker to respond to stock increases than declines (Rosenberg 2003) and regulatory changes often follow, rather than precede, stock declines (Matthiasson 2003). In an examination of four of Iceland’s most important fisheries, including herring, Matthiasson (2003) found that meaningful management reforms only occurred when the fishery had collapsed or was close to collapse, a pattern consistent with most major fisheries worldwide (Pauly et al. 2002; Rosenberg 2003). Historic failure of herring stock management has also been attributed to “doing too little too late” (Jakobsson 1985).

Regulatory mechanisms that guide exploitation of herring in Southeast Alaska are adopted through the BOF after consideration of biological, social, and economic factors. Scientific advice is provided through ADF&G’s analyses of proposals which conclude with Department support, opposition, or neutrality (ADF&G 2012f). Of 13 proposals relating to herring that the BOF voted upon in 2012, only one was carried against ADF&G opposition, albeit with some modification. Proposal 238 concerned the establishment of a subsistence-only area in Sitka Sound with waters closed to commercial fishing. The BOF discussion of this proposal included the need for reasonable opportunity for subsistence users to collect a herring quota, as well as to determine whether the area would prove to be a potential sanctuary for herring should boats normally scatter the fish as they stage prior to spawning.

6.4.2 Summary

Existing regulatory mechanisms offer some degree of protection for herring and their habitat in Southeast Alaska. Such measures include temporary restrictions put into place to protect spawning herring, such as timing windows for coastal construction projects, and fishery management measures defining the limitations of commercial harvest.

Regulations pertaining to the herring fishery are adopted by the Alaska Board of Fisheries, after consideration of social, political, and economic factors, as well as scientific input from ADF&G. The current Herring Management Plan regulates that ADF&G:

- identify stocks on a spawning areas basis. ADF&G currently manages nine separate spawning stocks of herring. While ADF&G considers the incidence of fish migration between stocks low, the movement of herring may be a complicated function of density-

dependent processes, geographic scale, environmental conditions and conspecific influence;
- establish a minimum spawning biomass threshold, below which fishing will not occur. Initial thresholds were based on historic knowledge, biologists' judgment and/or a quantitative method involving age-structured analysis, with thresholds set at 25% of the modeled average unfished biomass. In either case, given the significant shifts in herring populations and trophic level dynamics that were probable throughout the reduction fishery and commercial whaling, it is possible that the adopted threshold are not necessarily an accurate reflection of a historic equilibrium;
- assess the abundance of mature herring for each stock before allowing fishing to occur. ADF&G mainly uses BA and ASA modeling, based upon data collected from spawn deposition and other surveys, to forecast the following year's abundance of mature herring for each stock. Inaccuracies and uncertainties may arise from many different sources in this process and substantial discrepancies have occurred in the past between forecasted estimates and estimates based on actual spawning events. ADF&G relies on real-time biologist assessment on the fishing grounds to recognize these discrepancies and modify the fishery accordingly;
- except as provided elsewhere, allow a harvest of herring at an exploitation rate between 10 and 20 percent of the estimated spawning biomass when that biomass is above the minimum threshold level. Regulatory measures in place do not preclude an exploitation rate above 20% in certain circumstances;
- identify and consider sources of mortality in setting harvest guidelines. ADF&G uses ASA modeling to estimate natural survival (1 – natural mortality) as a single parameter averaged across the years for which age-specific data on herring abundance are available. These survival estimates may be adjusted or renewed according to trends that occur over blocks of time with indices, but the model does not apportion predation and disease as separate components of natural mortality nor does it forecast upcoming conditions; and
- by emergency order, may modify fishing periods to minimize incidental mortalities during commercial fisheries. Managers are expected to assess field conditions, recognize potential catastrophic stock changes as they occur, and modify limits accordingly.

Inadequacies of regulatory mechanisms that define limits of commercial exploitation are primarily in the form of uncertainties regarding: understanding of herring biology, including migration, recruitment and natural mortality, which significantly affect the accuracy of abundance assessment methods relative to true abundance; the accuracy of values for historical or baseline biomass; and the biological validity of thresholds and exploitation rates relative to an unknown extinction threshold. It is likely that such uncertainties are inherent in regulatory mechanisms of many commercial fisheries and not limited to ADF&G management of herring in Southeast Alaska.

6.5 Other Natural or Man-made Factors

6.5.1 Anthropogenic Climate Change

In 1988, the World Meteorological Organization and the United Nations Environmental Programme established the Intergovernmental Panel on Climate Change (IPCC) to provide an objective source of information concerning anthropogenic effects on global climate. According to the IPCC, changes in the atmospheric loading of greenhouse gases alter the energy balance of the climate system (IPCC 2007). The most important greenhouse gas driving the climate system change is carbon dioxide (CO_2), primarily from the burning of fossil fuels, deforestation, industrialization, cement production and other land-use changes (Guinotte and Fabry 2008). The IPCC considers warming of the climate system as unequivocal and projections of future climate change include the following phenomena:

- Further warming with patterns similar to those observed over the past several decades;
- Greater atmospheric carbon dioxide concentrations increasing ocean acidification; and
- Both past and future anthropogenic carbon dioxide contributing to warming and sea level rise for more than a millennium, due to the time scales required for removal of this gas from the atmosphere.

(IPCC 2007).

Throughout most of the North Pacific, models have indicated a spatially homogeneous and linear warming trend, liable to lead to an unprecedented state in a few decades with resultant impacts on ecosystems (Wang et al. 2010). Although variability in temperature and precipitation in Southeast Alaska is primarily influenced by random, interannual fluctuations resulting from recurring patterns such as the Pacific Decadal Oscillation or El Nino Southern Oscillation, longer term trends of warmer and wetter conditions in Southeast Alaska are likely. Some uncertainty results from a lack of long-term data. Nine weather stations throughout Southeast Alaska contribute to weather data published monthly by the National Climate Data Center; however, the earliest records only begin in 1922. Despite the lack of a significantly lengthy time series, some trends are apparent. Air temperature records from Sitka, which are representative of all stations since the 1950's, show a 0.45° C warming trend starting from the 1920's. This warming trend increases to 1.7° for the 1940's to 2000's (Fig. 39).

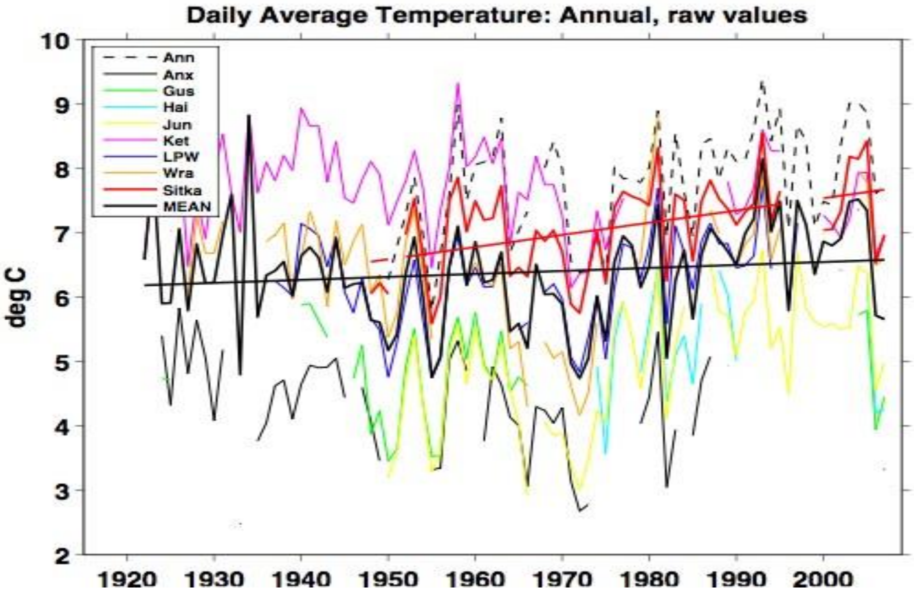
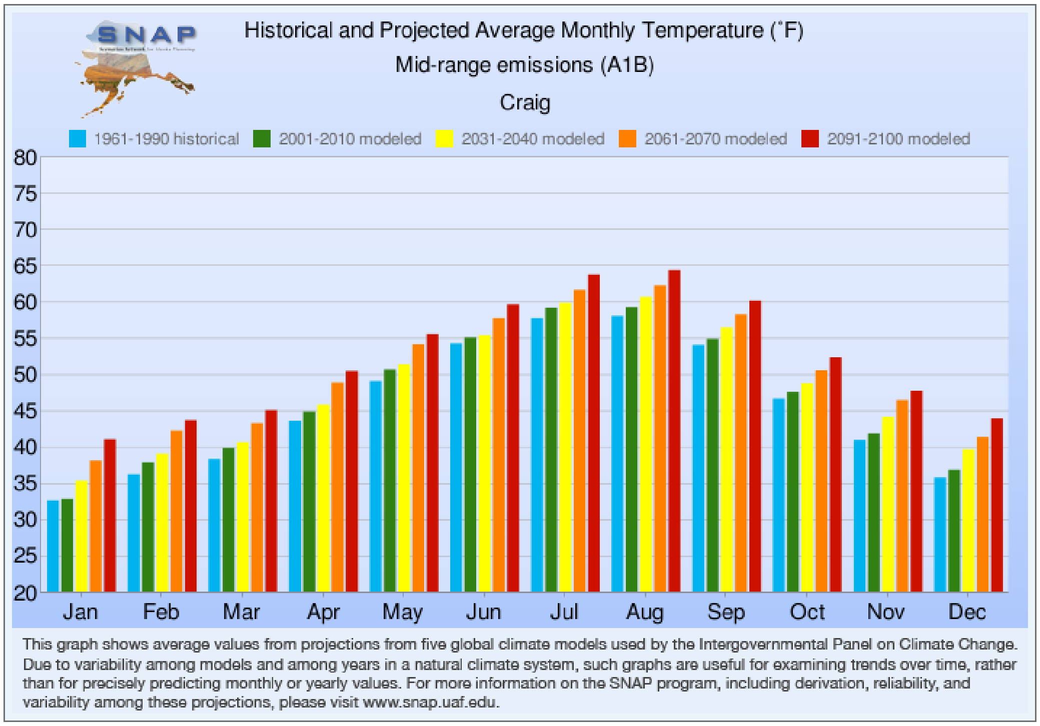


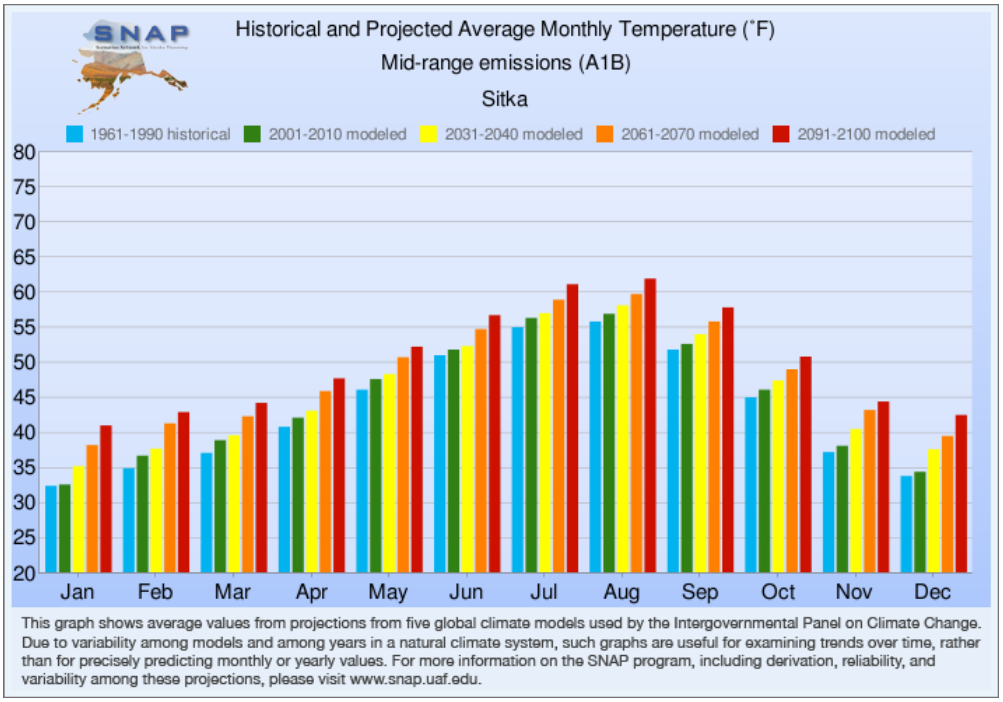
Figure 38. Annual mean air temperature for recording stations in Southeast Alaska and the all-station mean (black). Black and red lines show least-squares trend for all stations and Sitka, respectively (Cherry et al. 2010).

The average daily minimum winter temperature in Southeast Alaska has increased by 1.5° since the 1920's and 3.2° since the 1940's. The daily minimum temperatures in spring, summer and autumn have also increased since 1920 (Cherry et al. 2010). In Auke Bay, the slope of the trend line suggested SST increased between 1959 and 1975, although the increase was not statistically significant (Wing and Pella 1998). Between 1976 and 2004, the trend in sea surface temperature (SST) has increased about .024° C annually (Wing et al. 2006). Atmospheric warming is expected to continue (Figs. 40, 41). Precipitation is also expected to increase in Southeast Alaska (Figs. 42, 43) which, along with glacial melting, will contribute to ocean freshening along coastal areas.


Historical and Projected Average Monthly Temperature (˚F)
Mid-range emissions (A1B)
Craig

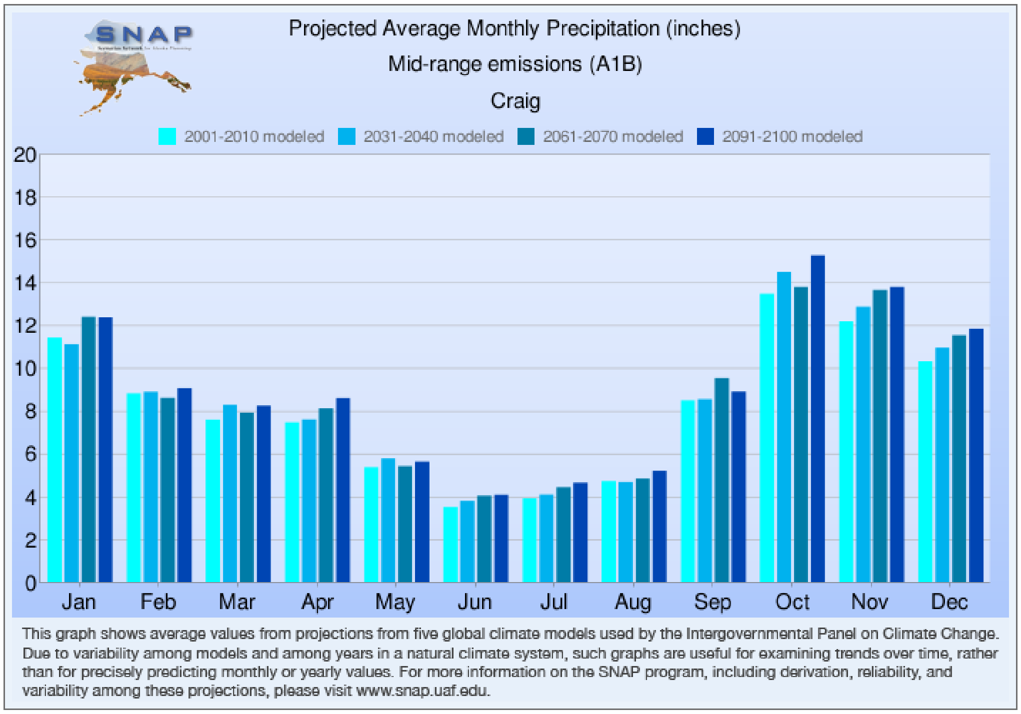
This graph shows average values from projections from five global climate models used by the Intergovernmental Panel on Climate Change. Due to variability among models and among years in a natural climate system, such graphs are useful for examining trends over time, rather than for precisely predicting monthly or yearly values. For more information on the SNAP program, including derivation, reliability, and variability among these projections, please visit www.snap.uaf.edu.

Figure 39. Historic and projected average monthly temperatures of Craig, AK given mid-range CO_2 emissions (SNAP 2011).



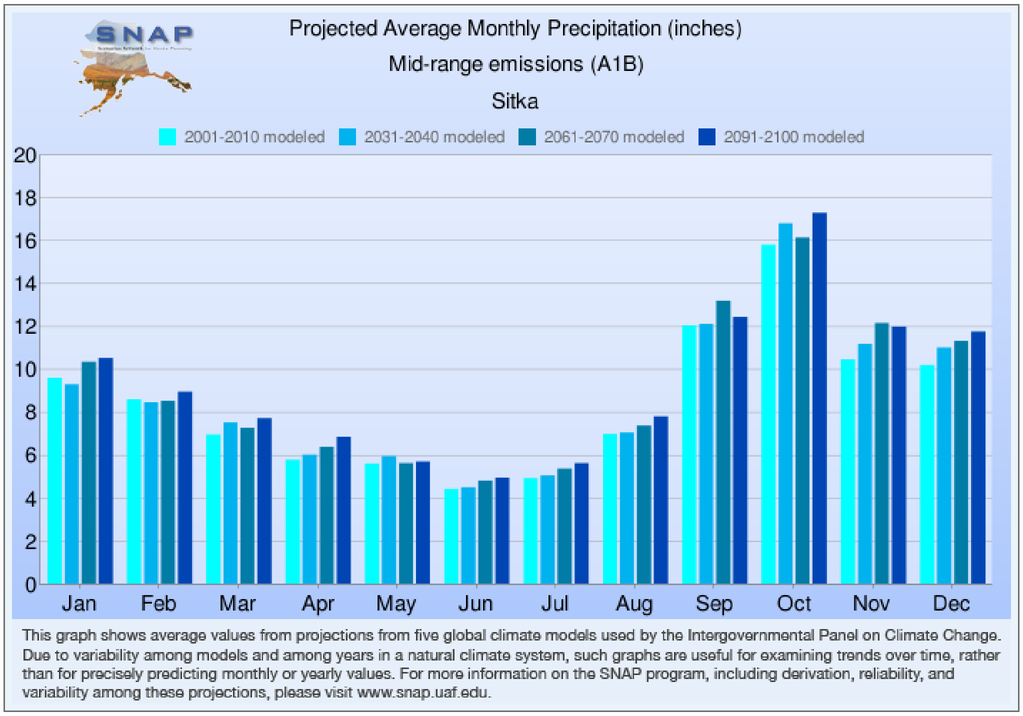
This graph shows average values from projections from five global climate models used by the Intergovernmental Panel on Climate Change. Due to variability among models and among years in a natural climate system, such graphs are useful for examining trends over time, rather than for precisely predicting monthly or yearly values. For more information on the SNAP program, including derivation, reliability, and variability among these projections, please visit www.snap.uaf.edu.

Figure 40. Historic and projected average monthly temperatures of Sitka, AK given mid-range CO_2 emissions (SNAP 2011).



This graph shows average values from projections from five global climate models used by the Intergovernmental Panel on Climate Change. Due to variability among models and among years in a natural climate system, such graphs are useful for examining trends over time, rather than for precisely predicting monthly or yearly values. For more information on the SNAP program, including derivation, reliability, and variability among these projections, please visit www.snap.uaf.edu.

Figure 41. Historic and projected average monthly precipitation of Craig, AK given mid-range CO_2 emissions (SNAP 2011).



This graph shows average values from projections from five global climate models used by the Intergovernmental Panel on Climate Change. Due to variability among models and among years in a natural climate system, such graphs are useful for examining trends over time, rather than for precisely predicting monthly or yearly values. For more information on the SNAP program, including derivation, reliability, and variability among these projections, please visit www.snap.uaf.edu.

Figure 42. Historic and projected average monthly precipitation of Sitka, AK given mid-range CO_2 emissions (SNAP 2011).

Concurrent with atmospheric and marine warming, ocean acidification from increasing global CO_2 is also of potential concern to the viability of marine fauna. Ocean acidification may be defined as the change in ocean chemistry driven by marine uptake of chemical inputs to the atmosphere, including carbon and, to a lesser extent, nitrogen and sulfur compounds (Guinette and Fabry 2008). An increase in anthropogenic CO_2 and subsequent uptake and dissolution in the oceans is expected to reduce ocean surface pH by 0.3 – 0.5 over the next century (Feely et al. 2004). Effects of ocean acidification may be especially pronounced in Alaskan coastal waters (Sewall et al. 2009), and recent evidence has shown that ocean acidification appears to be more severe and is occurring more rapidly in Alaska than in tropical waters (SFOS 2009).

The geochemical processes that drive pH changes may be predictable, but the impacts on marine biodiversity and ecosystems are highly uncertain (Herr and Galland 2009). Increased anthropogenic CO_2 may affect marine organisms through a variety of processes, both directly and indirectly, with potential impacts on multiple trophic levels (Orr et al. 2005; Brander 2010). The potential for increased CO_2 to impact a wide array of species on a physiological level has been shown (Shirayama and Thornton 2005; Langenbuch et al. 2006; Kurihara et al. 2008), including potential toxicity to eggs, larvae and adult marine fish (Ishimatsu et al. 2004). Studies have shown elevated CO_2 in fish may alter the acid-base balance, respiration, and circulation, and may lead to reduced growth rate and impaired reproduction (Ishimatsu and Kita 1999; Ishimatsu et al. 2004; Ishimatsu 2005). Reduced pH was also found to depress the growth and protein synthesis rates of developing herring embryos, and increased mortality at the lowest pH levels (Sewall et al. 2009).

Increased CO_2 can also alter ocean chemistry relating to the production of either calcite or aragonite, the two forms of calcium carbonate used by plankton, shellfish and fish to produce calcium carbonate shells and skeletons (Royal Society 2005; Fabry et al. 2008). Effects may be particularly swift in high-latitude ecosystems, with the decrease in calcium carbonate saturation potentially threatening key marine organisms, such as corals and some plankton, which are then unable to maintain external calcium carbonate skeletons. Evidence has shown that most marine calcifiers are sensitive to declines in carbonate saturation (Royal Society 2005; Kleypas et al. 2006; Guinotte and Fabry 2008) including reduced calcite production in both marine phytoplankton (Riebesell et al. 2000; Reibesell 2004) and shellfish (Gazeau et al. 2007). In higher latitudes, pteropods, which are the major planktonic producers of aragonite, may be especially vulnerable as they become unable to maintain shells in undersaturated waters. As pteropods form integral components of food webs and contribute to the diet of many marine species, including Pacific herring, effects may occur on multiple trophic levels (Fabry et al. 2008).

A great deal of uncertainty and informational gaps accompany predictions of ocean acidification. Researchers have no data on the ability of organisms to adapt or acclimate to shifting conditions or potential synergism between elevated CO_2 and other physical parameters such as light, nutrient base and temperature. In the Gulf of Alaska, for example, total freshwater discharge far exceeds other freshwater systems in North America (Royer and Grosch 2007) and species of zooplankton may be partially stratified by physical parameters such as temperature, depth and salinity (Coyle and Pinchuk 2005). While undersaturation is promoted by decreased salinity, alkalinity and dissolved inorganic carbon found with ocean freshening, as well as colder water (Yamamoto-Kawai et al. 2009), it is difficult to predict the magnitude of effects of future acidification/undersaturation on the abundance and composition of planktonic species in the region, including Southeast Alaska. Regardless of the level of uncertainty, preliminary evidence has shown that ocean acidification has the potential to reduce biodiversity in the ocean through a number of mechanisms, including the loss of species sensitive to changes in CO_2 and pH, the reduction of taxonomic diversity and the loss of keystone/critical species or a reduction in their activity (Widdicombe and Spicer 2008).

6.5.2 Regime Shifts

In the late 1970’s, particular climatic anomalies were noted throughout the North Pacific Ocean, including changes in sea surface temperature (SST), surface wind stress, sea level pressure (SLP), atmospheric circulation patterns, and advection patterns (Benson and Trites 2002). Evidence of a broad climatic change was substantial, including the analysis of a time series of 40 variables which showed a shift in 1976-77 by an amount averaging 4 to 7 times the interannual variability in both the preceeding and succeeding eight years (Ebbesmeyer 1991). There also appeared to be concurrent and unprecedented changes in the distribution, productivity and abundance of certain species of zooplankton, invertebrate and fish populations throughout the North Pacific (PICES 2005). The evidence of this community reorganization was compelling. In the Gulf of Alaska, for example, simultaneous declines were noted in both commercially and noncommercially utilized and ecologically disparate taxa such as crab, herring, eelpouts, and sablefish, while other, equally disparate, taxa such as groundfish and flatfish species, starfish, and cephalopods, increased in abundance (Anderson and Piatt 1999). By the 1990’s, the increasing volume of data linking climatic conditions and marine populations lead to the concept of “regimes”, defined as multi-year periods with linked recruitment patterns among populations or consistent conditions among physical data sets (Beamish et al. 1999). It also became apparent that 1976-77 was not unique in the historical record and that similar regime changes had previously occurred, and were still occurring. Historical data suggest changes may have occurred in 1925, 1947, 1977, 1989 and possibly 1998 (Mantua et al.1997; Hare and Mantua 2000; Benson and Trites 2002; Chavez et al. 2003). The result was the concept of "regime shifts", defined as low frequency, high amplitude, and sometimes abrupt, changes in species abundance, community composition, and trophic organization that occur concurrently with physical changes in a climate system (McKinnell et al. 2001). Because shifts appear to occur in a somewhat synchronous fashion, it is likely that a common event precipitates a regime shift, leading to long-term, nonrandom variations on a global scale; however, the precipitating cause of regime shifts has not been determined. Furthermore, while the 1976-77 shift was strongly evident, not all proposed years have been universally accepted as regime shifts (McFarlane et al. 2000).

The basis for a regime shift determination is made through analysis of various atmospheric, terrestrial, oceanic, and biological indices developed to assess the persistence and synchrony of change (Beamish et al. 1999; Hare and Mantua 2000; Benson and Trites 2002). A variety of major and minor indices are used to characterize climatic and oceanographic conditions of the Pacific, each incorporating particular physical parameters, such as SST, SLP, wind stress, ocean and atmospheric currents, or precipitation patterns.

Along with climatic indices, correlations between climatic conditions and productivity in a variety of fish species have also been used to characterize regime shifts (Hollowed and Wooster 1992; Francis and Hare 1994). For most major fisheries along the Pacific coast of Canada and the U.S., recruitment trends appear to correspond to climatic patterns, although some anomalous years are also apparent. Productivity trends appear to be in similar, but inexact, synchrony with patterns of the Aleutian Low Pressure Index (ALPI), i.e. lower mean pressures were associated with above-average year class survival for many species, with the opposite true for greater high pressures, indicating a dominant effect of winter atmospheric pressure on regional fish abundance in the North Pacific (Beamish 1993; Beamish and Bouillon 1995). Many fish species have been shown to respond synchronously with some species and asynchronously with other species. A synchrony between Atlantic and Pacific herring abundance fluctuations, for example, with opposing phases to the synchrony of Pacific sardines and European pilchards respectively, led to the conclusion that variation in sardine and herring were subject to global climatic changes (Kawasaki 1991). Shifts in diversity and abundance of zooplankton and phytoplankton have also been shown to correspond to regime shifts (Hare and Mantua 2000).

The presence of "biological domains" may, in part, explain geographical variation in fish abundance. Regions of the North Pacific have been characterized into specific oceanographic "domains" according to physical parameters such as seasonal heating and cooling, precipitation, evaporation and wind mixing. Ware and McFarlane (1989) assessed biological productivity and physical data and concluded the northeast Pacific contains three fish production domains, each unique relative to dominant fish species and their response to regime shifts. Southeast Alaska is considered part of the "coastal down-welling domain," which includes the continental shelf and coastal waters from Queen Charlotte Sound to Prince William Sound and along the Aleutian Islands. Primary fish species of this domain include herring, halibut, sablefish, coho and chinook salmon, with herring being the dominant pelagic species along the eastern boundary (Ware and

McFarlane 1989). Associated ocean currents primarily include the counterclockwise Alaska Gyre in the central Gulf of Alaska and the Alaska Coastal Current (ACC), which dominates coastal waters over the continental shelf as it flows north from the Columbia River to the Bering Sea (Reed and Schumacher 1986; Stabeno et al. 2004; Royer and Grosch 2007; Weingartner 2007a). Productivity in this domain includes mixed assemblages of oceanic and neritic zooplankton, which vary in part due to shoreward advection from upwelling processes and vertical mixing associated with the Alaskan Gyre (Brodeur and Ware 1992; Stabeno et al. 2004). Changes in flow of the ACC also appear to affect plankton biomass and, indirectly, fish recruitment variability (Ware and McFarlane 1989), with the current intensity varying seasonally and spatially, particularly due to water stratification dependent on freshwater runoff and wind-mixing (Weingartner et al. 1995). While the ACC is the primary ocean current in the area, bathymetric features such as troughs and canyons can also affect localized flow patterns, including the formation of cyclonic eddies within embayments that facilitate larval retention (Allen et al. 2001; Stabeno et al. 2004).

The ACC is driven mainly by the Aleutian Low (Stabeno et al. 2004), the dominant atmospheric pressure system in the northeast Pacific. Changes in the character of the Aleutian Low appear to be central to regime shift dynamics in the North Pacific (Beamish and Bouillon 1995; Hare and Mantua, 2000; McFarlane et al. 2000; Benson and Trites 2002). Along the Gulf of Alaska and in Southeast Alaska, a strong Aleutian Low is characterized by higher precipitation, higher SST, higher primary productivity, nutrient and zooplankton levels (Ware and McFarlane 1989; Brown 2002). Population dynamics of herring in the Gulf of Alaska have been found to correspond in part to intensification of the Aleutian Low, with increased precipitation and the resulting freshwater having a strong stabilizing effect on oceanographic conditions. Based on studies in Auke Bay, Alaska, a stable water column during the spring bloom helps structure the composition of the phytoplankton community (Ziemann et al. 1990; Bienfang and Ziemann 1995). However, while increased freshwater discharge along the Gulf of Alaska may increase water column stability, the concurrent changes in ocean current speed and direction may complicate spatial patterns in larval distribution and survival. While increased mean current flow may advect larvae away from preferred nursery habitats, eddies and other current instabilities that develop could also potentially lead to greater retention of larvae (Okkonen et al. 2003; Weingartner 2007b).

Although biological responses to regime shifts often lag behind, or are confounded by, changes in many other variables, one of the most important physical oceanographic variables that influence marine biology is SST. Herring production across the globe has long been associated with a number of variable climatic conditions, but perhaps especially with SST. Long-term fluctuations in the abundance of Norwegian spring-spawning herring appeared to be determined by the influence of climate on recruitment, with SST as a necessary but not sole parameter (Toresen and Ostvedt 2000). In the Hokkaido-Sakhalin stock of Pacific herring, low to near average SST was considered an important element in a suite of environmental factors needed to produce a strong year class (Nagasawa 2001). Herring spawn timing has been correlated to winter and spring SST (Haegele and Schweigert 1985; Lassuy 1989; Emmett et al. 1991; Brown and Carls 1998). In British Columbia, SST primarily during the winter was found to exert a significant influence on size-specific fecundity and egg size (Tanasichuk and Ware 1987). Herring growth may also be affected by SST, with temperature either positively or negatively affecting growth rate depending upon region and regime (Moores and Winter 1982; Ware 1991a, 1991a; Tanasichuk 1997; Schweigert et al. 2002; Rose et al. 2008).

Similarities in recruitment time series for Pacific herring also suggest populations may be grouped into large-scale associations based on responses to environmental influences, with temperature seeming to be more influential than other environmental parameters, although the mechanism is unclear (Williams and Quinn 2000b). Typically, a time series of Pacific herring recruitment is highly variable with large class events occurring at intervals of 3-9 years (Williams 1999). Large year class events can dominate the recruitment time series, with the ratio of largest year class to the weakest being > 400 (Zheng 1996). As delineated with SST records, similarities in herring recruitment in the northeast Pacific provide some evidence for the distinction of three separate populations, including a British Columbia group, a southeast Alaska coastal group, and an outer Gulf of Alaska group, which possibly indicates spatially synchronized responses to similar large-scale environmental influences (Williams 1999; Willams and Quinn 2000a). A common biological response over broad geographic regions may be an adaptive response to commonalities in local prey resources, competition, and associated climatic regimes (Hay et al. 2008). The response of Southeast Alaska coastal herring to a regime shift, therefore, may differ significantly from herring in other regions such as the Bering Sea or British Columbia (Hollowed and Wooster 1995; McFarlane et al. 2000; Williams and Quinn 2000a). Although herring did not appear to exhibit the same frequency of strong year classes as many other fish species between 1945 and 1989, strong year classes were evident in Canadian herring in 1970, 1971, 1977 and 1985 (Hollowed and Wooster 1995), whereas dominant year classes in Southeast Alaska herring were apparent in 1976, 1980, 1984 and 1988 (Zebdi and Collie 1995). In Southeast Alaska, recruitment has been positively correlated with temperature (Favorite and McLain 1973; Rounsefell 1930), possibly because warmer temperatures lead to earlier spawning and hatching that matches improved planktonic conditions in the Gulf of Alaska (Brodeur and Ware 1992; Benson and Trites 2002). In Sitka Sound herring, SST was found to be the physical parameter most highly correlated with recruitment, followed by an index for upwelling. Recruitment was positively correlated with warm, wet conditions (Zebdi and Collie 1995). Conversely, in southern British Columbia, warm conditions appeared to negatively affect herring year class strength though increased predation and decreased biomass of zooplankton (Ware 1991b; Schweigert 1995; Williams 1999).

6.5.3 Summary

Possible physical outcomes of global climate change from increased anthropogenic CO2 include an increase in water temperature and ocean acidification. Regime shifts include cyclical large scale changes in climate systems and significant reorganizations of marine communities. Both are associated with informational gaps as well as a corresponding uncertainty which arises from multiple sources:

- The inability to accurately predict the temporal and spatial effects of ocean warming and acidification and the adaptability of species to those effects.
- The inability to accurately predict climate, the impossibility of recognizing long-lived regime shifts at the time they occur and the likelihood that each regime shift will present a new set of conditions (Mantua et al. 1997; Benson and Trites 2002; Mantua and Hare 2002; Polovina 2005; Mueter et al. 2007) where biological variability may not linearly mimic decadal variations in climate forcing (Miller and Schneider 2000).

- The magnification of risks in the presence of covariation in stocks where the productivity of multiple stocks may be affected similarly and simultaneously (Beamish and Bouillon 1995; Mueter et al. 2007), including changes in predator abundance, distribution and impact (McFarlane et al. 2001; Benson and Trites 2002).
- The validity upon which management models and decisions are based, including stock recruitment relationships and the assumption of a baseline community or virgin unfished biomass (Steele 1996; Benson and Trites 2002).
- The underlying assumption of a stable equilibrium condition for a stock and ecosystem (May 1977).
- The inability to forecast the potential interplay of stressors such as climate change, fishing pressure, habitat loss etc. on populations (Chavez 2003). Because productivity varies with climate, the effects of fishing are concurrent with a natural regulation, although the latter may not be distinguishable or predictable.

Traditionally, fishing management aims to maintain populations at fixed levels with yields considered sustainable for an indefinite period of time. However, in the face of continuing ocean change, sustainability may be relative only to the current set of conditions. The most critical implications concern periods of low productivity (Mantua et al. 1997). With any sharp drops in production, management decisions are made regardless of the cause. However, if a regime shift has occurred, it may not be possible to rebuild the stock to previous levels as specific environmental conditions may be required. Stocks must then be managed for new levels of productivity (Beamish and Bouillon, 1995; Polovina 2005). True sustainability, therefore, may require avoiding a “steady state” management strategy (Simmonds 2007).

6.6 Summary of Threats

Herring is a keystone species in Southeast Alaska, playing a central role in marine food webs and also of significant importance as a commercial and subsistence species in many communities.

While the threats discussed above and listed below have been considered separately, herring population depletions may result from a series of compounded threats interacting within the environment (Schweigert et al. 2010). For example, the multiple facets of both anthropogenic climate change and regime shifts present serious challenges to fishery management goals of sustainability. While natural systems have adapted to climatic changes throughout history, the rate of climate change has accelerated as have the number of concurrent pressures, including fishing efficiency and habitat modification. Variations in ocean climate can moderate herring recruitment by alternating both predator and food abundance (Ware 1991a). Similarly, disease in the ocean is on the rise and can increase predation and contribute to population declines (Harvell et al. 1999, 2002). Links have been established between temperature and herring disease (Hedrick 2003; Gregg et al. 2011), which may then influence recruitment and adult population abundance of herring (Marty et al. 2010). All of the factors impacting herring, including the five listing factors, may synergistically compromise resilience.

Threats to herring may include:

- Habitat modification
  Both historically and currently, modification of herring habitat in Southeast Alaska has primarily occurred through chronic and localized, direct and indirect, impacts of human habitation, population growth and tourism. Impacts include increased shoreline modification, pollution, marine traffic and noise as well as the introduction of invasive species. However, characterizing the consequences of habitat modification relative to herring populations is challenging. It is probable that a complex synergy of both identified and unidentified factors link herring biology and the surrounding environment. For example, while both Auke Bay and Sitka Sound have experienced expanding human growth and activity, opposing trends have occurred in herring stock abundance.

- Overutilization
  Although overutilization has occurred in the history of commercial herring fishing in Southeast Alaska, especially during the reduction era, neither fishery nor biological reference points indicate that herring in Southeast Alaska are currently being overutilized. Evidence may indicate that herring abundance was historically greater and spawning locations more widespread and, under certain circumstances, this may be a cause for concern. However, this evidence is tempered by the uncertainty associated with (1) the potential for significant gaps in spawning location data; (2) the impacts on herring populations resulting from the historical decline of significant predators, including the humpback whale and Steller sea lion; and (3) the increasing biomass of the DPS as a whole.

- Disease or predation
  While disease may be a constant threat to herring stocks in Southeast Alaska, there is no evidence to indicate that the incidence of disease is increasing.

  Predation is a significant source of mortality throughout herring life history, with many species relying on herring as prey. However, trophic interactions, including predation and competition, are not easily characterized. Herring predation by some species, such as marine mammals, has been characterized more fully than with others, such as piscivorous fish. If the underlying assumption that predation increases with predator population is valid, which does appear to be the case with humpback whales, then at least two herring predators in Southeast Alaska, humpback whales and Steller sea lions, are likely to be increasing the predation pressure on herring in Southeast Alaska.

- Inadequacy of regulatory mechanisms
  Current regulatory mechanisms do not provide on-going protection for herring habitat. Inadequacies of regulatory mechanisms that define limits of commercial exploitation are primarily in the form of uncertainty regarding: understanding of herring biology, including migration, recruitment and natural mortality, which significantly affect the accuracy of abundance assessment methods relative to true abundance; the accuracy of values for historical or baseline biomass; and the biological validity of thresholds and exploitation rates relative to an unknown extinction threshold. It is likely that such

uncertainties are inherent in regulatory mechanisms of many commercial fisheries and not limited to ADF&G management of herring in Southeast Alaska.

- Other natural or man-made factors
  Both anthropogenic climate change and regime shifts are associated with a great deal of uncertainty relating both to physical and biological change as well as herring adaptability to change. Anthropogenic climate change includes ocean warming and acidification, both of which have the potential to significantly affect herring abundance. The threat of regime shifts lies primarily through the challenge to stock sustainability, with trophic shifts and fishing serving as multiple, synergistic stressors.

7.0 Extinction Risk Analysis

In assessing risk, it is important to include both qualitative and quantitative information, when feasible. The threats section supplied qualitative information on potential risks to Southeast Alaska herring. A quantitative assessment was then made through a risk matrix method, as described in detail by Wainright and Kope (1999). This method was used to quantitatively organize and summarize the professional judgment of an Extinction Risk Assessment (ERA) team composed of a panel of knowledgeable scientists. In the risk matrix approach, the ERA team assessed the condition of Southeast Alaska herring populations and summarized according to the following demographic risk criteria: abundance, growth rate/productivity, spatial structure/connectivity, and diversity as well as other modifying factors. These viability criteria, outlined in McElhany et al. (2000), reflect concepts that are well-founded in conservation biology and that individually and collectively provide strong indicators of extinction risk. After reviewing all the relevant commercial and biological data supplied in the threats section, the ERA team used these concepts to estimate the extinction risk of the Southeast Alaska DPS of Pacific herring based on current demographic risks. This approach and has been used in Pacific salmonid status reviews as well as in reviews of Pacific hake, walleye pollock, Pacific cod, Puget Sound rockfishes, Pacific herring, and black abalone (see http://www.nmfs.noaa.gov/pr/species/ for links to these reviews). The ERA team also completed a threats assessment by scoring the severity of current threats to the DPS as well as predicting whether the threat will increase, decrease, or stay the same in the foreseeable future. The ERA team then used the information to determine the DPS' overall level of extinction risk. A final task included the consideration as to whether the Southeast Alaska DPS of Pacific herring was at risk of extinction throughout all or a significant portion of its range (SPOIR).

7.1 Methods

7.1.1 Demographic Risks Analysis

After reviewing all relevant biological and commercial information for the species, each ERA team member assigned a risk score to each of the four demographic criteria (abundance, growth rate/productivity, spatial structure/connectivity, diversity) as well as other modifying factors. Risks were ranked on a scale of 1 (no or very low risk) to 5 (very high risk) based on the following definitions:

1 = No or very low risk: It is unlikely that this DPS is at risk of extinction due to projected threats or trends in abundance, productivity, spatial structure, or diversity.

2 = Low risk: It is unlikely that this DPS is at risk of extinction due to trends in abundance, productivity, spatial structure or diversity; however, current threats (or projected threats) may be (or will be) altering those trends but not yet by enough to cause the species to be influenced by stochastic or depensatory processes.

3 = Moderate risk: The DPS exhibits a trajectory indicating that it is approaching a level of abundance, productivity, spatial structure, and or/diversity that places its current or future persistence in question. A DPS may be at moderate risk of extinction due to declining trends in abundance, productivity, spatial structure, or diversity and current or projected threats that inhibit the reversal of these trends.

4 = High risk: The DPS is at or near a level of abundance, productivity, spatial structure, and or/diversity that places its current or future persistence in question. Similarly, it faces clear and present threats that are likely to create such demographic risks.

5 = Very high risk: The DPS is strongly influenced by stochastic or depensatory processes, facing current threats exacerbating the demographic risks, and indicating imminent extinction.

The team members were given a template to fill out and asked to rank current demographic risk as well as to provide comments in justification for their scores. The scores were then tallied (mode, median, range) and provided to the group, along with summarized commentary, for review.

7.1.2 Threats Assessment

Section 4(a)(1) of the ESA requires the agency to determine whether the species is endangered or threatened because of any of the following factors:

1) destruction or modification of habitat;
2) overutilization for commercial, recreational, scientific, or educational purposes;
3) disease or predation;
4) inadequacy of existing regulatory mechanisms; or
5) other natural or human factors.

After reviewing the best available scientific and commercial data on the Southeast Alaska DPS of Pacific herring, the ERA team identified and evaluated the following potential threats to the species: predation and disease; shoreline modification/urbanization, invasive species, pollution, marine traffic and noise; anthropogenic climate change and regime shifts; habitat protection and commercial fishery regulations; fishery reference points and biological reference points.

Similar to the demographics risk analysis, the ERA team members were given a template to fill out and asked to rank the current severity of the threats to the extinction risk of the DPS on a scale of 1 to 5 with the scoring criteria as follows:

1 = No or very low risk: It is unlikely that this factor contributes significantly to risk

of extinction, either by itself or in combination with other factors

2 = Low risk: It is unlikely that this factor contributes significantly to risk of extinction by itself, but some concern that it may, in combination with other factors.

3 = Moderate risk: It is likely that this factor in combination with others contributes significantly to risk of extinction.

4 = High risk: It is likely that this factor, by itself, contributes significantly to risk of extinction

5 = Very high risk: It is highly likely that this factor, by itself, contributes significantly to risk of extinction

On the same template, the ERA team was also requested to forecast whether these potential threats would increase (+), decrease (-), or stay the same (0) in the foreseeable future in ranking the severity of threats into the foreseeable future (up to 30 years). The foreseeable future was loosely determined to be approximately 3 generation times or about 30 years for herring, as equivalent to the time frame over which predictions about the future in making determinations about the future conservation status of the species can be reasonable relied upon (NMFS 2013). The template also included a comment section. The scores were then tallied (mode, median, range) and provided to the group, along with summarized commentary, for review.

7.1.3 Overall Level of Extinction Risk Analysis

This assessment was guided by the results of the risk matrix analysis, integrating information about demographic risks with expectations about likely interactions with threats and other factors. The ERA team members used their informed professional judgment to make an overall current extinction risk determination for the DPS. For these analyses, five levels of extinction risk were defined:

1 = No or very low risk: It is unlikely that this DPS is at risk of extinction due to projected threats or trends in abundance, productivity, spatial structure, or diversity.

2 = Low risk: It is unlikely that this DPS is at risk of extinction due to trends in abundance, productivity, spatial structure or diversity; however, current threats (or projected threats) may be (or will be) altering those trends but not yet by enough to cause the species to be influenced by stochastic or depensatory processes.

3 = Moderate risk: The DPS exhibits a trajectory indicating that it is approaching a level of abundance, productivity, spatial structure, and or/diversity that places its current or future persistence in question. A DPS may be at moderate risk of extinction due to declining trends in abundance, productivity, spatial structure, or diversity and current or projected threats that inhibit the reversal of these trends.

> 4 = High risk: The DPS is at or near a level of abundance, productivity, spatial structure, and or/diversity that places its current or future persistence in question. Similarly, it faces clear and present threats that are likely to create such demographic risks.
>
> 5 = Very high risk: The DPS is strongly influenced by stochastic or depensatory processes, facing current threats exacerbating the demographic risks, and indicating imminent extinction.

To allow individuals to express uncertainty in determining the overall level of extinction risk facing the species, the ERA team adopted the “likelihood point” method, used by other scientific teams in evaluating options (FEMAT 1993). This approach has been used in previous status reviews (e.g. Pacific salmon, Southern Resident Killer Whale, Puget Sound Rockfish, Pacific herring, and black abalone) to structure the team’s thinking and express levels of uncertainty in assigning risk categories. For this approach, each team member distributed 10 ‘likelihood points’ among the five levels of risks. The scores were then tallied and summarized.

7.1.4 SPOIR extinction risk assessment

The final task assigned to the ERA team was to determine whether the Southeast Alaska DPS of Pacific herring is at risk of extinction “throughout all or a significant portion of its range (SPOIR).” Team members were provided guidance in interpreting terminology related to SPOIR and also requested to answer the following question, “if the species were to become extirpated from all areas in which it is currently at risk, at that point would the entire species be at risk of extinction (or likely to become so)?” If so, then these areas may be considered a “significant portion of the species range”. ERA team members were provided a template in which to address the SPOIR issue which included a section for comments.

Finally, the ERA team did not make recommendations as to whether the species should be listed as threatened or endangered. Rather, the ERA team drew scientific conclusions about the overall risk of extinction faced by the species.

7.2 Extinction Risk Results and Conclusions

7.2.1 Evaluation of Demographic Risks (Table 3)

Abundance

ERA team scores for current abundance ranged from 1 to 2 with a modal and median score of 1. A score of 1 represents low or no risk, meaning that it is unlikely that the DPS is at risk of extinction due to projected threats or trends in abundance. The team was in general agreement that aggregations for which long-term spawning biomass data are available have either increased or fluctuated around a constant mean, but are not generally declining. Based on current trends, there appears to be no aggregation with an increased extinction risk due to depensatory processes or demographic stochasticity.

Growth rate/productivity

ERA team scores for current growth rate and productivity ranged from 1 to 2 with a modal and median score of 1. A score of 1 represents low or no risk, meaning that it is unlikely that this

DPS is at risk of extinction due to projected threats or trends in productivity. The team was in general agreement that the DPS is exhibiting positive trends in growth rate and productivity. Based on ASA estimates of recruitment and size-based parameters, productivity appears to be above replacement for assessed Southeast Alaska aggregations.

Spatial structure/connectivity

ERA team scores for the current spatial structure/connectivity of the DPS ranged from 1 to 3 with a modal score of 1 and a median score of 1.5. A score of 1 represents no or very low risk, meaning that it is unlikely that this DPS is at risk of extinction due to projected threats or trends in spatial structure/connectivity. A score of 3 represents a moderate risk, which means the DPS exhibits a trajectory indicating that it is approaching a level of spatial structure that places its current or future persistence in question. A DPS may be at moderate risk of extinction due to declining trends in spatial structure and current threats that inhibit the reversal of these trends.

While herring in the Southeast Alaska DPS are still relatively widespread, there is some uncertainty relative to the importance of current vs. historic patterns as herring spawning locations do not appear to be as widespread as they once were. Furthermore, several spawning stocks are concentrated near urban areas, and habitat constriction is a concern. Although urbanization is more likely to destroy rather than create herring habitat, it is also probable that many suitable, unused spawning locations currently exist.

While the spatial structure among different life history stages of Pacific herring in Southeast Alaska is not well defined, evidence suggests intermixing among spawning and non-spawning populations. Existing data may be limited and inconclusive, but there is also little evidence to suggest the existence of a critical source population or that migration among stocks is unidirectional. Stock structure appears to be poorly defined at the spatial scales <250 km, suggesting a high degree of stock mixing. Although local spawning aggregations may periodically exhibit low levels of biomass and abundance (e.g., Tenakee Inlet), these aggregations appear to rebuild in time, possibly due to immigration from other spawning aggregations. Based on acoustics surveys of abundance throughout the winter and spring, it has been hypothesized that mature herring from multiple stocks in inside waters of Southeast Alaska inhabit the deep trenches of southern Lynn Canal in the winter. In the spring, this large over-wintering school disperses to their respective spawning grounds. Herring from inside waters may be non-migratory and spend their life in inside waters, while those adjacent to the open ocean (Sitka) likely move offshore in the summer to feed. Although this co-mingling of stocks occurs in the winter during the non-breeding period, it shows there is some degree of connectivity amongst spawning stocks.

There are also indications of mixing on a broader scale. Fish from Sitka Sound appear to be more similar to herring in Prince William Sound rather than herring in the inside waters of northern southeast Alaska, suggesting that when the migratory stocks on the outer coast move offshore to feed in the summer, there could be some dispersal or connectivity. On the southern border, there are spawning stocks of herring in close proximity (~35 km) to Kah Shakes in Chatham Sound, Canada, and the coastline is comprised of herring habitat, including many protected bays and passageways. While natural rates of dispersal are unknown, dispersal is also possible to the south.

Diversity

ERA team scores for current diversity ranged from 1 to 2 with a modal and median score of 1. A score of 1 represents low or no risk, meaning that it is unlikely that this DPS is at risk of extinction due to projected threats or trends in diversity. While not all spawning aggregations are monitored, there is currently no evidence to suggest a substantial change or loss of variation in life-history traits, population demography, morphology, behavior or genetic characteristics.

Relevant modifying factors

ERA team scores ranged from 1 to 2 with a modal and median score of 1. One member abstained from adding a score on the grounds that, while no relevant modifying factors were present, the absence of modifying factors did not fit the prescribed scoring system. The team cited a number of relevant modifying factors. While herring are considered resilient, low recruitment, likely stemming from infrequent conditions that support rapid population increases, was a concern. The potential for increased disease prevalence with herring pounds was also of concern as was site fidelity in areas of no habitat protection and increased urbanization and development.

Demographic Risk	Mode	Median	Range
Abundance	1	1	1 - 2
Growth rate/productivity	1	1	1 - 2
Spatial structure/connectivity	1	1.5	1 - 3
Diversity	1	1	1 - 2
Relevant modifying factors	1	1	1 - 3

Table 3. Scores indicating demographic risk.

7.2.2 Evaluation of Threats (Table 4)

The following table provides the results of the ERA team's analysis of the severity of threats to the Southeast Alaska DPS of Pacific herring.

Threat	Current			Future		
	Mode	Median	Range	Mode	Median	Range
Predation	2	2.5	1 - 3	0	0	- to 0
Disease	1	1.5	1 - 3	0	0	- to +
Shoreline modification/urbanization	2	2	2 - 3	+	+	0 to +
Invasive species	1	1	1	0, +	0, +	0 to +
Pollution	1	1	1 - 3	+	+	0 to +
Marine traffic and noise	1	1	1 - 2	+	0, +	- to +
Anthropogenic climate change	1	1	1 - 2	0, +	0, +	0 to +
Regime shifts	1	1	1 - 2	0	0	0
Habitat protection	2.5	2.5	2 - 3	+	+	- to +
Commercial fishery regulations	2	2	1 - 3	0	0	- to 0
Fishery reference points	1	1	1 - 2	0	0	- to 0
Biological reference points	1.5	1.5	1 - 2	0	0	- to 0

Table 4. Scored severity of threats to Southeast Alaska herring

None of the assigned scores indicated a level of risk which places the current or future persistence of the DPS into question. The ERA team assigned the greatest risk, which was scored as low to moderate, to habitat protection followed by predation, shoreline modification and commercial fishery regulations. The latter threats all had a low to moderate (predation) or low (shoreline modification, commercial fishery regulations) median score with a range from no/very low risk to moderate risk. Legal protection of spawning and nursery habitats was considered important, especially with respect to increased urbanization and other stressors associated with human activity. The populations of several large predators, and potential impacts on herring, were recognized to be increasing; however, it was considered likely that prey bases would shift before local extinction occurred.

7.2.3 Overall Risk Summary

This assessment was guided by the results of the risk matrix analysis, integrating information about demographic risks with expectations about likely interactions with threats and other factors. The ERA team distributed most of the "likelihood points" (27/40) to the no/low level of extinction risk, meaning that it was considered unlikely that this DPS is at risk of extinction due to projected threats or trends in abundance, productivity, spatial structure, or diversity. Fewer points (12/40) were assigned to the low risk category, which means that, while it is unlikely that the DPS is at risk of extinction due to trends in abundance, productivity, spatial structure or diversity, current threats may be altering those trends, but not yet by enough to cause the species to be influenced by stochastic or depensatory processes.

Risk level				
No or low (1)	**Low (2)**	**Moderate (3)**	**High (4)**	**Very high (5)**
10				
1	8	1		
8	2			
8	2			

Table 5. Scores indicating current overall level of extinction risk.

7.2.4 SPOIR Extinction Risk Summary

Team members uniformly decided that the Southeast Alaska DPS of Pacific herring was not at risk of extinction throughout all or a significant portion of its range. Although substantial reductions occurred historically, the basic functioning of the DPS as a metapopulation does not appear to be seriously impaired in any portion of its range. While different spawning aggregations may exhibit different short-term trends, biomass data have either increased or fluctuated, but are not generally declining.

8.0 Glossary

List of Common/Scientific Names

Marine mammals

Dall’s porpoise - *Phocoenoides dalli*
Fin whale - *Balaenoptera physalus*
Gray whales – *Eschrichtius robustus*
Harbor porpoise - *Phocoena phocoena*
Harbor seal - *Phoca vitulina*
Humpback whale - *Megaptera novaeangliae*
Killer whales - *Orcinus orca*
Minke whale - *Balaenoptera acutorostrata*
Pacific white-sided dolphin - *Lagenorhynchus obliquidens*
Steller sea lion - *Eumetopias jubatus*

Birds

Bald eagle - *Haliaeetus leucocephalus*
Black turnstone - *Arenaria melanocephala*
Common murre - *Uria aalge*
Glaucous-winged gull - *Larus glaucescens*
Harlequin duck - *Histrionicus histrionicus*
Marbled murrelet - *Brachyramphus marmoratus*
Mew gull - *Larus canus*
Pelagic cormorant - *Phalacrocorax pelagicus*
Surfbird - *Aphriza virgata*
Surf scoter - *Melanitta perspicillata*
White-winged scoters - *Melanitta fusca*

Fishes and Invertebrates

Arrowtooth flounder - *Atheresthes stomias*
Atlantic herring - *Clupea harengus*
Capelin - *Mallotus villosus*
Great sculpin - *Myoxocephalus polyacanthocephalus*
Greenling species - *Hexagrammos lagocephalus, Hexagrammus decagrammus*
Leather star - *Dermasterias imbricata*
Lingcod - *Ophiodon elongatus*
Pacific cod - *Gadus macrocephalus*
Pacific hake - *Merluccius productus*
Pacific halibut - *Hippoglossus stenolepis*
Pacific sandfish - *Trichodon trichodon*
Pacific sand lance - *Ammodytes hexapteras*
Sablefish - *Anoplopoma fimbria*
Chinook salmon - *Oncorhynchus tshawytscha*
Chum salmon – *Oncorhynchus keta*
Coho salmon - *Oncorhynchus kisutch*
Pink salmon - *Oncorhynchus gorbuscha*
Spiny dogfish - *Squalus acanthias*
Steelhead trout - *Oncorhynchus mykiss*
Turban snail - *Astrea gibberosa*
Walleye Pollock – *Theragra chalcogramma*

9.0 Literature Cited

ACOE (Army Corps of Engineers). January 30, 2012. Letter from Sitka Regulatory Field Office to Mr. Gordon Rush.

ADCCED (Alaska Department of Commerce, Community, and Economic Development. 2007. Alaska Visitor Statistics Program, Summer 2006. McDowell Group, Juneau, Anchorage. 166 p.

ADCCED (Alaska Department of Commerce, Community, and Economic Development. 2011. Alaska Visitor Statistics Program VI Interim Visitor Volume Report, Summer 2010. McDowell Group, Juneau, Anchorage. 8 p.

ADEC (Alaska Department of Environmental Conservation). 2009a. Salt Chuck Mine and Mill Area. ADEC Contaminated Sites Program. 6 p.

ADEC (Alaska Department of Environmental Conservation). 2009b. Alaska DEC large cruise ship 2008 wastewater sampling results. 25 p.

ADEC (Alaska Department of Environmental Conservation). 2010a. Alaska’s final 2010 integrated water quality monitoring and assessment report. July 2010. 142 p.

ADEC (Alaska Department of Environmental Conservation). 2010b. ADEC Large Commercial Passenger Vessel Wastewater Discharge, General Permit No. 2009DB0026. Marine Discharge of Treated Sewage and Treated Graywater from Commercial Passenger Vessels Operating in Alaska. 45 p.

ADEC (Alaska Department of Environmental Conservation). 2010c. 2010 Large Commercial Passenger Vessel Wastewater Discharge General Permit Information Sheet. Permit No. 2001DB0026. April 22, 2010. 33 p.

ADEC (Alaska Department of Environmental Conservation). 2012. Nonpoint Source Water Pollution Control. http://dec.alaska.gov/water/wnpspc/index.htm (Accessed 10/11/2012).

ADF&G (Alaska Department of Fish and Game). 1985. Subject: Herring Thresholds. Memo from Don Ingledue, Area Management Biologist to Paul Larson, Finfish Coordinator, April 19, 1985.

ADF&G (Alaska Department of Fish and Game). 2000. Southeast Alaska Sac Roe Herring Fishery 2000 Management Plan, Regional Information report No. 1J00-07, Feb. 2000. 16 pp.

ADF&G (Alaska Department of Fish and Game). 2000a. Southeast Alaska Sac Roe Herring Fishery 2000 Management Plan. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report No. 1J00-07.

ADF&G (Alaska Department of Fish and Game). 2007. State response to requests for information, FR 72, No. 174 (Sept. 10, 2007) re LC herring. 1514-12-a-02-g; Pacific Herring Listing; Public Comment C009.

ADF&G (Alaska Department of Fish and Game). 2010a. Recent Harvest and Status. Accessed at:http://www.cf.adfg.state.ak.us/geninfo/finfish/herring/herring_harvest.php#catch,(Accessed 1/8/2010).

ADF&G (Alaska Department of Fish and Game). 2010b. Advisory Committee Manual. http://www.adfg.alaska.gov/index.cfm?adfg=process.advisory (Accessed 2/29/2012)

ADF&G (Alaska Department of Fish and Game). 2010c. Advisory Committees. http://www.boards.adfg.state.ak.us/advisory/index.php (Accessed 12/15/2010).

ADF&G (Alaska Department of Fish and Game). 2010d. Division of Commercial Fisheries News Release, Sitka Sound Sac Roe Herring Fishery Announcement, Dec. 16, 2010.

ADF&G (Alaska Department of Fish and Game). 2011. Board of Fisheries Proposal Book.http://www.adfg.alaska.gov/static/regulations/regprocess/fisheriesboard/pdfs/2011-2012/2011_2012prop_book.pdf (Accessed 2/17/2012).

ADF&G (Alaska Department of Fish and Game). 2012a. Alaska's Fisheries and Game Board Process. http://www.adfg.alaska.gov/index.cfm?adfg=process.main (Accessed 2/22/2012).

ADF&G (Alaska Department of Fish and Game). 2012b. Welcome to the Board of Fisheries! http://www.adfg.alaska.gov/index.cfm?adfg=fisheriesboard.main (Accessed 2/22/2012).

ADF&G (Alaska Department of Fish and Game). 2012c.Board of Fisheries 2011-2012 Proposal Book http://www.adfg.alaska.gov/index.cfm?adfg=fisheriesboard.main (Accessed 2/27/2012).

ADF&G (Alaska Department of Fish and Game). 2012d.Alaska Board of Fisheries Members. http://www.adfg.alaska.gov/index.cfm?adfg=fisheriesboard.bofmembers (Accessed 3/3/2012).

ADF&G (Alaska Department of Fish and Game). 2012e.Alaska Board of Fisheries Meeting Information: Summary of Actions. http://www.adfg.alaska.gov/index.cfm?adfg=fisheriesboard.meetinginfo (Accessed 5/1/2012).

ADF&G (Alaska Department of Fish and Game). 2012f. Staff comments on commercial, sport, subsistence, and personal use finfish regulatory proposals, committee of the whole, committees A, B, C and D for Southeast Alaska and Yakutat finfish management areas. Regional Information Report No. 1J12-01. 437 p.

ADF&G (Alaska Department of Fish and Game). 2012g. Division of Commercial Fisheries News Release, Sitka Sound Sac Roe Herring Fishery Announcement, March 8, 2012.

ADF&G (Alaska Department of Fish and Game). 2012h. Division of Commercial Fisheries News Release, Sitka Sound Sac Roe Herring Fishery Announcement, April 12, 2012.

ADF&G (Alaska Department of Fish and Game). 2013. ADF&G Comments on NOAA Fisheries Draft SEAK Herring Stock Status Report (version received by department on May 8, 2013). 16 p.

ADLWD (Alaska Department of Labor and Workforce Development). 2012. DLWD Research and Analysis, Population estimates. Accessed at: http:laborstats.alska Gov/pop/popest.htm (1/31/2013).

AND (Anchorage Daily News). Iceland investigating mass herring deaths. Accessed at: http://www.adn.com/search_results?q=herring (2/6/2013).

Agler, B.A., S.J. Kendall, D.B. Irons, and S.P. Klosiewski. 1999. Declines in marine bird populations in Prince William Sound, Alaska coincident with a climatic regime shift. Waterbirds 22:98-0103.

Alderdice, D.F., and A.S. Hourston. 1985. Factors influencing development and survival of Pacific herring (*Clupea harengus pallasi*) eggs and larvae to beginning of exogenous feeding. Canadian Journal of Fisheries and Aquatic Science 42(Suppl.1):56–68.

Allen, B.M. and R.P. Angliss. 2011. Alaska Marine Mammal Stock Assessments, 2010. NOAA Technical Memorandum NMFS-AFSC-223. 297 pp.

Allen, B.M. and R.P. Angliss. 2012. Alaska Marine Mammal Stock Assessments, 2011. NOAA Technical Memorandum NMFS-AFSC-234. 293 pp.

Allen, S.E., C. Vindeirinho, R.E. Thomson, M.G.G. Foreman, and D.L. Mackas. 2001. Physical and biological processes over a submarine canyon during an upwelling event. Canadian Journal of Fisheries and Aquatic Sciences 58: 671-684.

Anderson, C.N.K., C. Hsieh, S. A. Sandin, R. Hewitt, A. Hollowed, J. Beddington, R. M. May and G. Sugihara. 2008. Why fishing magnifies fluctuations in fish abundance. Nature 452, 835-839

Anderson, E.M., J.R. Lovvorn, D. Esler, W.S. Boyd, and D.R. Nysewander. 2005. The value of herring spawning events to spring conditioning of scoters in the Puget Sound Georgia Basin. *In*: Proceedings, Second North American Sea Duck Conference, USGS Patuxent Wildlife Research Center, Annapolis, MD. 123 p.

Anderson, E.M., J.R. Lovvorn, D. Esler, S. Boyd, and K.C. Stick. 2009. Using predator distributions, diet and condition to evaluate seasonal foraging sites: sea ducks and herring spawn. Marine Ecology Progress Series 386:287-302.

Anderson, P.J. and J.F. Piatt. 1999. Community reorganization in the Gulf of Alaska following ocean climate regime shift. Marine Ecology Progress Series, 189: 117–123.

Andrews, R.C. 1909. Observations on the habits of the finback and humpback whales of the eastern North Pacific. Bulletin of the American Museum of Natural History 26: 213 -226.

Anthony, J.A., D.D. Roby and K.R. Turco. 2000. Lipid content and energy density of forage fishes from the northern Gulf of Alaska. Journal of Experimental Marine Biology and Ecology 248:53-78.

Arai, M.N., and D.E. Hay. 1982. Predation by Medusae on Pacific herring (*Clupea harengus pallasi*) larvae. Canadian Journal of Fisheries and Aquatic Science 39:1537-1540.

Aydin, K. Y., S. Gaichas, I. Ortiz, D. Kinzey, and N. Friday. 2007. A comparison of the Bering Sea, Gulf of Alaska, and Aleutian Islands large marine ecosystems through food web modeling. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-AFSC-178. 298 p.

Bailey, J.E., B.L. Wing and C.R. Mattson. 1975. Pink salmon, *Oncorhynchus gorbuscha*, and chum salmon, *Oncorynchus keta*, in Traitors Cove, Alaska, with speculations on the carrying capacity of the area. Fishery Bulletin 73:8467-861.

Baker, C.S., L.M. Herman, A. Perry, W.S. Lawton, J.M. Straley and J.H. Straley 1985. Population characteristics and migration of summer and late-season humpback whales (*Megaptera novaeangliae*) in southeastern Alaska. Marine Mammal Science 1: 304-323

Baker, C.S., J.M. Straley and A. Perry. 1992. Population characteristics of individually identified humpback whales in southeastern Alaska: summer and fall 1986. Fishery Bulletin, U.S. 90:429 – 437.

Bakun, A. 2006. Wasp-waist populations and marine ecosystem dynamics: Navigating the "predator pit" topographies. Progress in Oceanography, 68(2-4), 271-288.

Baraff, L.S., and T.R. Loughlin. 2000. Trends and potential interactions between pinnipeds and fisheries of New England and the U.S. West Coast. Marine Fisheries Review 62:1–39.

Barlow, J., J. Calambokidis, C.S. Baker, A.M. Burdin, P.J. Clapham, J.K. Ford, C.M. Gabriele, R. LeDuc, D.K. Mattila, T.J. Quinn, L. Rojas-Bracho, J.M. Straley, B.L. Taylor, J. Urban R., P. Wade and D. Weller. 2011. Humpback whale abundance in the North Pacific estimated by photographic capture-recapture with bias correction from simulation studies. Marine Mammal Science 27:793-818.

Barron, M.G., M.G. Carls, J.W. Short, and S.D. Rice. 2003. Photoenhanced toxicity of aqueous phase and chemically dispersed weathered Alaska North Slope crude oil to Pacific herring eggs and larvae. Environmental Toxicology and Chemistry 22:650–660.

Bayer, R.D. 1980. Birds feeding on herring eggs at the Yaquina Estuary, Oregon. Condor 82:193–198.

Beamish, R. 1993. Climate and exceptional fish production off the west coast of North America. Canadian Journal of Fisheries and Aquatic Science 50:2270–2291.

Beamish, R.J., and D.R. Bouillon. 1995. Marine fish production trends off the Pacific coast of Canada and the United States. *In* Climate change and northern fish populations, pp 585–591. Ed. By R. Beamish, Canadian Special Publication of Fisheries and Aquatic Sciences 121.

Beamish, R.J., D.J. Noakes, G.A. McFarlane, L. Klyashtorin, V.V. Ivanov, and V. Kurashov. 1999. The regime concept and natural trends in the production of Pacific salmon. Canadian Journal of Fisheries and Aquatic Science, 56:516-526.

Benson, A.J., and A.W. Trites. 2002. Ecological effects of regime shifts in the Bering Sea and eastern North Pacific Ocean. Fish and Fisheries 3:95–113.

Bergmann, W., Davidson, W., Gordon, D., Monagle, K. and S. Walker. 2008 Southeast Alaska Sac Roe Herring Fishery Management Plan. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report No. 1J08-09.

Bergmann,W., W. Davidson, D. Gordon, K. Monagle and S. Walker. 2009 Southeast Alaska Sac Roe Herring Fishery Management Plan. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report No. 1J09-02.

Berkeley, S.A., M.A. Hixon, R.J. Larson and M.S. Love. 2004. Fisheries Sustainability via Protection of Age Structure and Spatial Distribution of Fish Populations. Fisheries 29: 23 – 32.

Beverton, R.J.H. 1990. Small marine pelagic fish and the threat of fishing; are they endangered? Journal of Fish Biology 37(Supplement A):5–16.

Bianchi, G, H. Gislason, K. Graham, L. Hill, X. Jin, K. Sainsbury, F. Sanchez and K. Zwanenburg.2000.Impact of fishing on size composition and diversity of demersal fish communities. ICES Journal of Marine Science 57: 558- 571.

Bienfang, P.K., and D.A. Ziemann. 1995. APPRISE: A multi-year investigation of environmental variation and its effects on larval recruitment. Climate change and northern fish populations. Canadian Special Publication of Fisheries and Aquatic Science 121: 483-487.

Bishop, M.A. and S.P. Green. 1999. Sound Ecosystem Assessment (SEA): Avian predation on herring spawn in Prince William Sound. Restoration project 96320-Q final report to Exxon Valdez Oil Spill Restoration Council. 78 pp.

Bishop, M.A., and S.P. Green. 2001. Predation on Pacific herring (*Clupea pallasi*) spawn by birds in Prince William Sound, Alaska. Fisheries Oceanography 10 (Suppl. 1):149-158.

Bishop, M.A., and S. Powers. 2010. PWS Herring Survey: Top-down regulation by predatory fish on juvenile herring in Prince William Sound. EXXON Valdez Oil Spill Trustee Council, Annual Project Report, Project No. 10100132-G. 4 p.

Bishop, M.A., J.T. Watson, K. Kuletz and T. Morgan. *Submitted.* Pacific herring consumption by marine birds during winter in Prince William Sound. Fisheries Oceanography.

Blanchard, J.L., N.K. Dulvy, S. Jennings, J.R. Ellis, J.K. Pinnegar, A. Tidd and L.K. Kell. 2005. Do climate and fishing influence size-based indicators of Celtic Sea fish community structure? ICES Journal of Marine Science 62:405-411

Blankenbeckler, D. 1978a. Pacific Herring (*Clupea pallasii*) Harvest statistics and a summary of hydroacoustical surveys conducted in southeastern Alaska during the fall, winter and spring, 1976-1977. Alaska Department of Fish and Game Technical Data Report No. 38. Juneau, AK. 150 p.

Blankenbeckler, D. 1978b. Pacific Herring (*Clupea pallasii*) Spawning Ground Research in Southeastern Alaska, 1977. Alaska Department of Fish and Game Technical Data Report No. 37. Juneau, AK. 17 p.

Blankenbeckler, D. and R. Larson. 1982. Pacific Herring (*Clupea pallasii*) Harvest Statistics and a Summary of Hydroacoustical Surveys Conducted in Southeastern Alaska during the Fall, Winter and Spring of 1977-78, 1978-79, and 1979-80. ADF&G Technical Data Report No. 70. Juneau, AK. 232 p.

Blankenbeckler, Dennis and Robert Larson. 1985. Herring spawning threshold levels, Southeast Alaska 1985. Alaska Department of Fish and Game Region I unpublished report, Ketchikan.

Bond, N., and J. Overland. 2009. North Pacific climate overview. *In* Ecosystem Considerations for 2010, pp 29–38. Edited by J. Boldt and S. Zador Stock Assessment and Fishery Evaluation Report. North Pacific Fishery Management Council, Anchorage, AK.

Boswell, K., J.J. Vollenweider and R. Heintz. 2009. Contrasting biomass estimates of schooling herring with an imaging sonar and traditional echosounder. Gulf of Alaska – Fish and Fish Habitat, Alaska Marine Science Symposium, Jan. 2010.

Bowen, W.D. 1997. Role of marine mammals in aquatic ecosystems. 1997. Marine Ecology Progress Series 158:267–274.

Brander, K. 2010. Impacts of climate change on fisheries. Journal of Marine Systems 79:389-402.

Breese, J.,K. Clark, E. Coonradt, D. Gordon, D. Harris, B. Meredith, K. Monagle, T. Thynes and S. Walker. 2012. 2012 Southeast Alaska herring spawn-on-kelp pound fishery management plan. Alaska Department of Fish and Game Regional Information Report No. 12-03. 39 p.

Breese, J.,K. Clark, E. Coonradt, D. Gordon, D. Harris, B. Meredith, K. Monagle, T. Thynes and S. Walker. 2010. 2010 Southeast Alaska herring spawn-on-kelp pound fishery management plan. Alaska Department of Fish and Game Regional Information report No. 1J10-02. 36 p.

Brock, M. and P. Coiley-Kenner. 2009. A Compilation of Traditional Knowledge about the Fisheries of Southeast Alaska. Alaska Department of Fish and Game, Division of Subsistence Technical Paper No. 332, Juneau. 53 p.

Brockman, S., and E. Grossman. 2010. A survey of herring spawning habitat on the new Thompson Harbor breakwaters, Sitka, Alaska. US Fish and Wildlife Service Report, Juneau, AK. 30 p.

Brodeur, R.D., E.A. Daly, M.V. Sturdevant, T.W. Miller, J.H. Moss, M. Thiess, M. Trudel, L.A. Weitkamp, J. Armstrong, and E.C. Norton. 2007. Regional comparisons of juvenile salmon feeding in coastal marine waters off the west coast of North America. *In* Ecology of juvenile salmon in the Northeast Pacific Ocean: regional comparisons, pp 183-203. Edited by C.B. Grimes, R.D. Brodeur, L.J. Haldorson, and S.M. McKinnell. American Fisheries Society, Symposium 57, Bethesda, Maryland.

Brodeur, R.D, and D.M. Ware. 1992. Long-term variability in zooplankton biomass in the subarctic Pacific Ocean. Fisheries Oceanography 1:32–38

Browman, H.I. and K.I. Stergiou. 2004. Perspectives on ecosystem-based approaches to the management of marine resources. Marine Ecology Progress Series 274:269-303.

Brown, E.D. 2002. Effects of climate on Pacific herring, *Clupea pallasii*, in the northern Gulf of Alaska and Prince William Sound, Alaska. *In* PICES-GLOBEC International Program on Climate Change and Carrying Capacity: Report of the 2001 BASS/MODEL, MONITOR and REX Workshops, and the 2002 MODEL/REX Workshop, pp 44–47. Edited by H.P. Batchelder, G.A. McFarlane, G.A., B.A. Megrey, D.L. Mackas, D.L. and W.T. Peterson, PICES Sci. Rep. No. 20.

Brown, E.D, and M.G. Carls. 1998. Pacific herring (*Clupea pallasi*). Rest Notebook, EVOSTC: 1-8.

Brown, E.D., J. Seitz, B.L. Norcross and H. Huntington. 2002. Ecology of herring and other forage fish as recorded by resource users of Prince William Sound and the outer Kenai Penninsula. Alaska Fishery Research Bulletin 9: 75-101

Brylinsky, C.K., K. Carroll, M. Vaughn, J. Stahl, A. Sayer, and D. Holum. 2008. 2009 Report to the Alaska Board of Fisheries, Groundfish Fisheries, Region 1: Southeast Alaska – Yakutat. Fishery Management Report 08-64, Anchorage. 47 p.

Bullard, S.G., G. Lambert, M.R. Carmen, J. Byrnes, R.B. Whitlatch, G. Ruiz, R.J. Miller, L. Harris, P.C. Valentine, J.S. Collie, J. Pederson, D.C. McNaught, C.N. Cohen, R.G. Asch, J. Dikstra, and K. Heinonen. 2007. The colonial ascidian *Didemnum* sp. A: current distribution, basic biology and potential threat to marine communities of the northeast and west coasts of North America. Journal of Experimental Marine Biology and Ecology 342:99–108.

Bundy A., J.J. Heymans, L. Morissette and C. Savenkoff . 2009. Seals, cod and forage fish: a comparative exploration of variations in the theme of stock collapse and ecosystem change in four northwest Atlantic ecosystems. Progress in Oceanography 81: 188−206.

Burger, A.E. 1997. Behavior and numbers of marbled murrelets measured with radar. Journal of Field Ornithology 68:208-223.

Calambokidis, J., E.A. Falcone, T.J. Quinn, A.M. Burdin, P.J. Clapham, J.K.B. Ford, C.M. Gabriele, R. LeDuc, D. Mattila, L. Rojas-Bracho, J.M. Straley, B.L. Taylor, J. Urban R., D. Weller, B.H. Witteveen, M. Yamaguchi, A. Bendlin, D. Camacho, K. Flynn, A. Havron, J. Huggins and N. Maloney 2008. SPLASH: Structure of populations, levels of abundance and status of humpback whales in the North Pacific. Final Report for US DOC Contract No. AB133F-03-RP-0078. 57 pp.

Caltrans (State of California, Department of Transportation). 2010. Storm water quality handbook: project planning and design guide. CTSW-RT-10-254.03.

Carlile, D., Larson, R. and T. Minicucci. February 1996. Stock Assessments of Southeast Alaska Herring in 1994 and Forecasts for 1995 Abundance. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Report No. 1J96-05.

Carlile, D. 1998a. Estimation and Evaluation of a Harvest Threshold for a Sitka Herring Sac Roe Fishery Based on a Percentage of Average Unfished Biomass. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report No. 1J98-18.

Carlile, D. 1998b. Estimation and Evaluation of a Harvest Threshold for a Tenakee Inlet Bait Fishery Based on a Percentage of Average Unfished Biomass. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report No. 1J98-18.

Carlile, D. 2003. Estimation and Evaluation of a Harvest Threshold for a W. Behm Canal Herring Fishery Based on a Percentage of Average Unfished Biomass. ADF&G Regional Information report No. 1J03-02. January 2003. 22 pg.

Carls, M.G., G.D. Marty, T.R.Meyers, R.E. Thomas, and S.D. Rice. 1998. Expression of viral hemorrhagic septicemia virus in prespawning Pacific herring (*Clupea pallasii*) exposed to weathered crude oil. Canadian Journal of Fisheries and Aquatic Sciences 55:2300-2309.

Carls, M.G., S.D. Rice, and J.E. Hose. 1999. Sensitivity of fish embryos to weathered crude oil: Part 1. Low-level exposure during incubation causes malformations, genetic damage, and mortality in larval Pacific herring (*Clupea pallasi*). Environmental Toxicology and Chemistry 18:481–493.

Carls, M.G., G.D. Marty, and J.E. Hose. 2002. Synthesis of the toxicological impacts of the Exxon Valdez oil spill on Pacific herring (*Clupea pallasi*) in Prince William Sound, Alaska, U.S.A. Canadian Journal of Fisheries and Aquatic Sciences 59:153–172.

Carls, M.G., S.W. Johnson, M.R. Lindeberg, A.D. Neff, P.M. Harris, R.S. Waples, J.T. Fujioka, R.G. Gustafson, E. Phillips, S.D. Rice, J. Vollenweider, B.L. Wing, and J.N. Womble. 2008. Status review of Lynn Canal herring (*Clupea pallasii*), Alaska Fisheries Science Center, Juneau, AK, 155 p.

Carlson, H.R. 1977. Results of a tagging study of Pacific herring in southeastern Alaska in 1960-62 using radioactive body tags. Northwest and Alaska Fisheries Center Report, Seattle WA.

Carlton, J.T., J.B. Geller, M.L. Reaka-Kudla, and E.A. Norse. 1999. Historical extinctions in the sea. Annual Review of Ecology and Systematics 30:515-538.

Carroll, K., and C.K. Brylinsky. 2010. The Southeast Alaska Northern Southeast Inside sablefish fishery information report, with outlook to the 2010 fishery. Fishery Management Report No.10-40, Anchorage. 50 p.

Carter H. R., and S. G. Sealy. 1990. Daily Foraging Behavior of Marbled Murrelets. Studies in Avian Biology 14:93–102

Chavez, F.P., J. Ryan, S.E. Lluch-Cota, and M. Niquen., 2003. From anchovies to sardines and back: Multidecadal change in the Pacific Ocean. Science 299:217–221.

Chambers, R. C., and W. C. Leggett. 1996. Maternal influences on variation in egg sizes in temperate marine fishes. American Zoologist 36:180–196.

Cherry, J.E., S. Walker, N. Fresco, S. Trainor and A. Tidwell. 2010. Impacts of climate change and variability on hydropower in Southeast Alaska: Planning for a robust energy future. Report to NOAA –NMFS Hydropower Coordination Office: 28 p.

Chilton, G., and S.G. Sealy. 1987. Species roles in mixed-species feeding flocks of seabirds. Journal of Field Ornithology 58:456-463.

Clapham, P.J. and J.G. Mead. 1999. *Megaptera novaeangliae*. Mammalian Species 604:1-9.

Cleaver, F.C., and D.M. Franett. 1946. The predation by sea birds upon the eggs of Pacific herring (*Clupea pallasi*) at Holmes Harbor during 1945. Washington State Department of Fisheries Biological Report 46B. 18 p.

Cohen, C.S.,L. McCann, T. Davis, L. Shaw, and G. Ruiz. 2011. Discovery and significance of the colonial tunicate *Didemnum vexillum* in Alaska. Aquatic Invasions 6:263–271.

Col, L.A., J.S. Link, S.X. Cadrin, D.L. Palka. 2012. Estimating consumption by marine mammals on the Northeast US continental shelf. IWC 2012 Annual Meeting of the Scientific Committee, Panama City, Panama, June 11-23, 2012. IWC SC/64/EM. 52 p.

Cooney, R.T., J.R. Allen, M.A. Bishop, D.L. Eslinger, T. Kline, B.L. Norcross, C.P. McRoy, J. Milton, J. Olsen, V. Patrick, A.J. Paul, D. Salmon, D. Scheel, G.L. Thomas, S.L. Vaughan and T.M. Willette. 2001. Ecosystem controls of juvenile pink salmon (*Oncorynchus gorbuscha*) and Pacific herring (*Clupea pallasi*) populations in Prince William Sound, Alaska. Fisheries Oceanography 10 (Suppl.1):1-13.

Corten, A. 2002. The role of “conservatism” in herring migrations. Reviews in Fish Biology and Fisheries 11:339-361.

Costello, M.J., and J.C. Gamble.1992. Effects of sewage sludge on marine fish embryos and larvae. Marine Environmental Research 33:49–74.

Cotter, A.J., L. Burt, C.G. Paxton, C. Fernanez, S.T. Buckland and J.X. Pan. 2004. Are stock assessment methods too complicated? Fish and Fisheries 5:235-254.

Coyle, K.O. and A.I. Pinchuk. 2005. Seasonal cross-shelf distribution of major zooplankton taxa on the northern Gulf of Alaska shelf relative to water mass properties, species depth preferences and vertical migration behavior. Deep-Sea Research II, 52: 217-245.

Csepp, D., J.J. Vollenweider, and M. Sigler. 2011. Seasonal abundance and distribution of pelagic and demersal fishes in southeastern Alaska. Fisheries Research 108:307–320.

Cury, P., A. Bakun, R.J. Crawford, A. Jarre, R.A. Quinones, L.J. Shannon and H.M. Verheye. 2000. Small pelagics in upwelling systems: patterns of interaction and structural changes in “wasp-waist” ecosystems. ICES Journal of Marine Science 57:603-618.

Cury, P.M., I.L. Byod, S. Bonhommeau, T. Anker-Nilssen, R.J.M. Crawford, R.W. Furness, J.A. Mills, E. J. Murphy, H. Osterblom, M. Paleczny, J.F. Piatt, J. Roux, L. Shannon, W.J. Sydeman. 2011. Global Seabird Response to Forage Fish Depletion – One-Third for the Birds. Science 334: 1703-1706.

Cury, P., and L. Shannon, L. 2004. Regime shifts in upwelling ecosystems: Observed changes and possible mechanisms in the northern and southern Benguela. Progress in Oceanography, 60:223–243.

Cushing, D. H. and R. R. Dickson. 1976. The biological response in the sea to climatic changes. Advances in Marine Biology 14: 1-122.

Dahlheim, M.E., P.A.White and J.M. Waite. 2009. Cetaceans of Southeast Alaska: distribution and occurrence. Journal of Biogeography 36: 410-426.

Daskalov, G.M. , A. N. Grishin, S. Rodionov, and V. Mihneva. 2007. Trophic cascades triggered by overfishing reveal possible mechanisms of ecosystem regime. PNAS 104 (25): 10518-10523.

Davidson, B.., D. Gordon, K. Monagle, T. Thynes and S. Walker. 2011. 2010 Southeast Alaska commercial herring fishery annual management report. Fishery Management Report No. 11-41. 44 p.

DeArmond, R.N. 1997. Baranof Island's Eastern Shore: The Waterfall Coast. Arrowhead Press, Sitka AK.

DeMaster, D.P., C. Marzin and R.J. Jameson. 1996. Estimating the historical abundance of sea otters in California. Endangered Species Update 13:79-81.

Denney, N.H., S. Jennings, and J.D. Reynolds. 2002. Life-history correlates of maximum population growth in marine fishes. Proceedings of the Royal Society, Biological Sciences 269:2229-2237.

Dixon, P.F., S. Feist, E. Kehoe, L. Parry, D.M.Stone, and K. Way. 1997. Isolation of viral hemorrhagic septicemia virus from Atlantic herring *Clupea harengus* from the English Channel. Diseases of Aquatic Organisms 30: 81-89.

Dolphin, W.F. 1987. Prey densities and foraging of humpback whales, *Megaptera novaeangliae*. Experientia 93: 468-471.

Donahue, M.J. 2006. Alee effects and conspecific cueing jointly lead to conspecific attraction. Oecologia 149:33-43

Dragesund O., J. Hamre and O. U. Lltang. 1980. Biology and population dynamics of the Norwegian spring-spawning herring. Rapp. P.-V. Reun.Cons. Int. Explor. Mer 177: 43-71.

Dragoo, D.E., H.M. Renner and D.B. Irons. 2012. Breeding status, populations trends and diets of seabirds in Alaska, 2009. U.S. Fish and Wildlife Service Report AMNWR 2012/01. Homer, Alaska. 108 p.

Dressel, S., Hebert, K., Pritchett, M. and D. Carlile. 2006. Southeastern Alaska Herring. In 2006 North Pacific Groundfish Stock Assessment and Fishery Evaluation. Reports for 2007. Appendix C: Ecosystem Considerations for 2007, p 180 – 184. Edited by J. Boldt. Alaska Fisheries Science Center,7600 Sand Point Way NE, Seattle, WA.

Duckett, K., D. Otte, J. Peckham, G. Pryor, A. McGregor, R. Holmes, S. Leask, D. Aho, G, Whistler, K. McDougal, A. Andersen, B. Pfundt, and E. Prestegard. 2010. Comprehensive salmon enhancement plan for Southeast Alaska: Phase III. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report No. 5J10-03, Juneau. 296 p.

Du Dot, T.J., D.A. Rosen, and A.W. Trites. 2008. Energy reallocation during and after periods of nutritional stress in Steller sea lions: Low-quality diet reduces capacity for physiological adjustments. Physiological and Biochemical Zoology 82:516–530.

Dulvy, N.K., J.R. Ellis, N.B. Goodwin, A. Grant, J.D. Reynolds, and S. Jennings. 2004. Methods of assessing extinction risk in marine fishes. Fish and Fisheries 5:255-275.

Dulvy, N.K. 2003. Extinction vulnerability in marine populations. Fish and Fisheries 4:25-64.

Duncan, D. and M. Carls. 2012. Are creosote pilings a hazard to herring embryos? Alaska Marine Science Symposium. Gulf of Alaska – Fish and Fish Habitat. 2012.

Ebbesmeyer, C.C., D.R. Cayan, D.R.McLain, F.H. Nichols, D.H. Peterson, and K.T. Redmond. 1991. 1976 step in the Pacific climate: forty environmental changes between 1968-1975 and 1977-1984. *In* Proceeding of the Seventh Annual Climate (PACLIM) Workshop, pp 115–126. Edited by J.L. Betancourt and V.L. Tharp. California Department of Water Resources, Interagency Ecological Studies Program Technical Report 26.

Einer-Jensen, K., Ahrens, P., Forsberg, P. and R. Lorenzen. 2004. Evolution of the fish rhabdovirus viral haemorrhagic septicaemia virus. Journal of General Virology 85: 1167-1179.

Elston, R.A. and T.R. Meyers, 2009. Effect of viral hemorrhagic septicemia virus on Pacific herring in Prince William Sound, Alaska, from 1985 to 2005. Diseases of Aquatic Organisms 83: 223–246.

Emmett, R. L., S.L. Stone, S.A. Hinton, and M.E. Monaco. 1991. Distribution and abundance of fishes and invertebrates in West Coast estuaries, Volume II: species life history summaries. ELMR. Rockville, MD, NOAA/NOS SEA Division: 329 p.

Engelhard, G.H. and M. Heino. 2004. Maturity changes in Norwegian spring-spawning herring *Clupea harengus*: compensatory or evolutionary responses? Marine Ecology Progress Series 272:245-256.

Engelhard, G.H. and M. Heino. 2006. Climate change and condition of herring (*Clupea harengus*) explain long-term trends in extent of skipped reproduction. Oecologia 149:593-603.

EPA (U.S. Environmental Protection Agency). 2001. National management measures guidance to control nonpoint source pollution from marinas and recreational boating. EPA 841-B-01-005. Washington, DC.

EPA (U.S. Environmental Protection Agency). 2003. Protecting water quality from urban runoff. EPA 841-F-03-003. Washington DC.

EPA (U.S. Environmental Protection Agency). 2010. Managing Nonpoint Source Pollution from Boating and Marinas. http://www.epa.gov/owow/nps/facts/point9.htm. (Accessed 6/9/2010).

Fabry, V.J., B.A. Seibel,R.A. Feely and J.C. Orr. 2008. Impacts of ocean acidification on marine fauna and ecosystem processes. ICES Journal of Marine Science, 65: 414-432.

Fabry, V., J. McClintock, J. Mathis, and J. Grebmeier. 2009. Ocean acidification at high latitudes: the bellwether. Oceanography 22:160–171.

Fagan, W.F. and E.E. Holmes. 2006. Quantifying the extinction vortex. Ecology Letters, 9:51-60.

Feely, R.A., C.L. Sabine, K. Lee, W. Berelson, J. Kleypas, V.J. Fabry and F.J. Millero. 2004. Impact of anthropogenic CO_2 on the $CaCO_3$ systems in the oceans. Science, 305: 362-266.

FEMAT (Forest Ecosystem Management Assessment Team). 1993. Forest ecosystem management: An ecological, economic, and social assessment. USDA Forest Service, BLM, USFWS, NOAA, EPA, and National Park Service, Portland, Oregon.

FOC (Fisheries and Ocean Canada). 2010. Background: Pacific Herring. http://www.pac.dfo-mpo.gc.ca/science/species-especes/pelagic-pelagique/herring\hareng/herspawn/pages/indicator-eng.htm (Accessed 12/18/2010)

Ford, K.B. and G.M. Ellis. 2006. Selective foraging by fish-eating killer whales *Orcinus orca* in British Columbia. Marine Ecology Progress Series 316:185-199.

Ford, J.K.B., G.M. Ellis, L.G. Barrett-Lennard, A.B. Morton, R.S. Palm and K.C. Balcomb. 1998. Dietary specialization in two sympatric populations of killer whales (*Orcinus orca*) in coastal British Columbia and adjacent waters. Canadian Journal of Zoology 76: 1456-1471.

Francis, R.C, and S.R. Hare. 1994. Decadal-scale regime shifts in the large marine ecosystems of the northeast Pacific: a case for historical science. Fisheries Oceanography 3:279–291.

Francis, R.C., M. A. Hixon, M. E. Clarke, S. A. Murawski and S. Ralston. 2007. Ten Commandments for Ecosystem-Based Fisheries Scientists. Fisheries 32(5): 217-233

Frank, K.T. and D. Brickman. 2000. Allee effects and compensatory dynamics within a stock complex. Canadian Journal of Fisheries and Aquatic Science 57:513-517.

Freon, P., F. Gerlotto, and M. Soria. 1992. Changes in school structure according to external stimuli – description and influence on acoustic assessment. Fisheries Research 15:45–66.

Freon, P., P. Cury, L. Shannon and C. Roy. 2005. Sustainable exploitation of small pelagic fish stocks challenged by environmental and ecosystem changes: A review. Bulletin of Marine science 76 (2): 385-462.

Fresh, K.L., R.D. Cardwell, and R.P. Koons. 1981. Food habits of Pacific salmon, baitfish and their potential competitors and predators in the marine waters of Washington, August 1978 to September 1979. State of Washington Department of Fisheries, Progress Report No. 145. 58 p.

Fried, S.M. and V.G. Wespestad. 1985. Productivity of Pacific herring (*Clupea harengua pallasi*) in the eastern Bering Sea under various patterns of exploitation. Canadian Journal of Fisheries and Aquatic Science 42 (S1):181-191.

Fu, C., J. Schweigert and C.C. Wood. 2004. An evaluation of alternative age-structured models in risk assessment of Pacific herring stocks in British Columbia. Fisheries and Oceans Canada, Research Document 2004/011, 55 p.

Fuiman, L.A. 1989. Vulnerability of Atlantic herring larvae to predation by yearling herring. Marine Ecology Progress Series 51:291-199.

Funk, F. and K.A. Rowell. 1995. Population Model Suggests New Threshold for Managing Alaska's Togiak Fishery for Pacific Herring in Bristol Bay. Alaska Fishery Research Bulletin 2 : 125 – 136.

Gannon, D.P., J.E. Craddock and A.J. Read. 1998. Autumn food habits of harbor porpoises, *Phocoena phocoena,* in the Gulf of Maine. Fishery Bulletin 96: 428-437.

Gazeau, F., C. Quiblier, J.M. Jansen, J. Gattuso, J.J. Middleburg and C.H.R. Heip. 2007. Impact of elevated CO_2 on shellfish calcification. Geophysical Research Letters, 34: 5 p.

Getz, W.M., R.C. Francis and G.L. Swartzman. 1987. On managing variable marine fisheries. Canadian Journal of Fisheries and Aquatic 44: 1370-1375.

Gende, S.M., and M.F. Sigler. 2006. Persistence of forage fish "hot spots" and its association with foraging Steller sea lions (*Eumetopias jubatus*) in Southeast Alaska. Deep-Sea Research II 53:432–441.

Grass, A. 1973. Mew gulls and black turnstones feeding on herring eggs. The Murrelet 54:38-39.

Gregg, J.L., J.J. Vollenweider, C.A. Grady, R.A. Heintz and P.K. Hershberger. 2011. Effects of Environmental Temperature on the Dynamics of Ichthyophoniasis in Juvenile Pacific herring (*Clupea pallasii*). Journal of Parasitology Research Vol. 2011, 9 p.

Guenette, S., S.J.J. Heymans, V. Christensen, and A.W. Trites. 2006. Ecosystem models show combined effects of fishing, predation, competition, and ocean productivity on Steller sea lions (*Eumetopias jubatus*) in Alaska. Canadian Journal of Fisheries and Aquatic Sciences 63:2495-2517.

Guinotte, J.M. and V.J. Fabry. 2008. Ocean acidification and its potential effects on marine ecosystems. Annals of the New York Academy of Science, 1134: 32–342.

Haegele, C.W. 1993b. Epibenthic invertebrate predation of Pacific herring, *Clupea pallasi*, spawn in British Columbia. Canadian Field-Naturalist 107:83-91.

Haegele, C.W. 1993. Seabird predation of Pacific herring, *Clupea pallasi*, spawn in British Columbia. Canadian Field Naturalist 107:73-82.

Haegele, C.W., and J.F. Schweigert. 1985. Distribution and characteristics of herring spawning grounds and description of spawning behavior. Canadian Journal of Fisheries and Aquatic Science 42:39–55.

Haegele, C.W., and J.F. Schweigert. 1989. Egg loss from Pacific herring spawns in Barkley Sound in 1988. Canadian Manuscript Report of Fisheries and Aquatic Science No. 2037. 37 p.

Haist, V., D.A. Fournier and J.F. Schweigert. 1993. Estimation of density-dependent natural mortality in British Columbia herring stocks through SSPA and its impact on sustainable harvesting strategies. *In* Risk evaluation and biological reference points for fisheries management, p 269-282. Edited by S.J. Smith, J.J. Hunt and D. Rivard. Canadian Special Publication Fisheries and Aquatic Science 120.

Haldorson, L., and J. Collie. 1990. Distribution of Pacific herring larvae in Sitka Sound, Alaska. *In* Proceedings of the International Herring Symposium, p 115–126. Edited by V. Wespestad, J. Collie and E. Collie. Alaska Sea Grant College Program AK-SG- 91-01.

Harnik, P.G., C. Simpson and J.L. Payne. 2012. Long-term differences in extinction risk among seven forms of rarity. Proceedings of the Royal Society, B 279:4969-4976.

Hart, J. 1973. Pacific fishes of Canada. Fisheries Research Board of Canada. Bulletin 180. Ottawa, Ontario.

Harvell, C.D., C.E. Mitchell, J.R. Ward, A.P. Dobson, R.S. Ostfeld and M.D. Samuel. 2002. Climate Warming and Disease Risks for Terrestrial and Marine Biota. Science 296: 2158 – 2162.

Harvell, C.D., K. Kim, J.M. Burkholder, R.R. Colwell, P.R. Epstein, D.J. Grimes, E.E. Hofmann, E.K. Lipp, A.D. Osterhaus, R.M. Overstreet, J.W. Porter, G.W. Smith and G.R. Vasta. 1999. Emerging Marine Diseases – Climate Links and Anthropogenic Factors. Science 285: 1505 - 1510.

Hawley, L.M. and K.A. Garver. 2008. Stability of viral hemorrhagic septicemia virus (VHSV) in freshwater and seawater at various temperatures. Diseases of Aquatic Organisms 82:171-178.

Hare, S.R. 2010. Assessment of the Pacific halibut stock at the end of 2009. International Pacific Halibut Commission, Report of Assessment and Research Activities 2009:91-170.

Hare, S.R., and N.J. Mantua. 2000. Empirical evidence for North Pacific regime shift in 1977 and 1989. Progress in Oceanography 47:103–145.

Hart, J. L. 1973. Pacific fishes of Canada. Bulletin 180. Ottawa, ON, Fisheries Research Board of Canada. 740 pp.

Hay, D.E. 1985. Reproductive biology of Pacific herring. Canadian Journal of Fisheries and Aquatic Science 42 (Suppl. 1): 111-126.

Hay, D.E. and A.R. Kronlund. 1987. Factors affecting thre distribution, abundance and measurement of Pacific herring (*Clupea harengus pallasi*) spawn. Canadian Journal of Fisheries and Aquatic Science 44:1181-1194.

Hay, D.E. and P.B. McCarter. 2011. Herring spawning areas of British Columbia, revised edition. Original edition: Hay, D.E., P.B. McCarter, R. Kronlund and C. Roy. 1989. Spawning areas of British Columbia herring: a review, geographical analysis and classification. Canadian Manuscript Report of Fisheries and Aquatic Science 1-6:2019

Hay, D.E., P.B. McCarter and K.S. Daniel. 2001. Tagging of Pacific herring *Clupea pallasi* from 1936–1992: a review with comments on homing, geographic fidelity, and straying. Canadian Journal of Fisheries and Aquatic Sciences 58:1356–1370.

Hay, D.E. and S.M. McKinnell. 2002.Tagging along: association among individual Pacific herring (*Clupea pallasi*) revealed by tagging. Canadian Journal of Fisheries and Aquatic Science 59:1960-1968.

Hay, D. E. and D. N. Outram 1981. Assessing and monitoring maturity and gonad development in Pacific herring. Canadian Technical Report Fisheries and Aquatic Sciences 988: 1.

Hay, D.E, K.A. Rose, J. Schweigert, and B.A. Megrey. 2008. Geographic variation in North Pacific herring populations: Pan-Pacific comparisons and implications for climate change impacts. Progress in Oceanography 77:233–240.

Hay, D., R. Toresen, R. Stephenson, M. Thompson, R. Claytor, F. Funk, J. Jakobsson, T Kobayashi, I. McQuinn, G. Melvin, J. Molloy, N. Naumenko, K. Oda, R. Parmanne, M. Power, V. Radchenko, J. Schweigert, J., Simmonds, B. Sjostrand, D. Stevenson, R. Tanisichuk, Q. Tang, D. Walters, and J. Wheeler. 2001a. Taking stock: an inventory and review of world herring stocks in 2000, p 381 – 455. *In* Herring: Expectations for a New Millenium. Edited by F. Funk, J. Blackburn, D. Hay, A.J. Paul, R. Stephenson, R. Toresen, and D. Witherell. Alaska Sea Grant College program, AK-SG-01-04.

HDR. 2010. Statter Harbor Improvements Project. Draft Environmental Assessment. HDR Alaska, Inc. Anchorage, AK. 120 p.

Hebert, K. 2011.2012 Report to the Alaska Board of Fisheries: Southeast Alaska – Yakutat Herring Fisheries. Alaska Department of Fish and Game, Division of Commercial Fisheries, Fishery management report 11-74.

Hebert, K. 2009. Southeast Alaska 2009 Herring Stock Assessment Surveys. Alaska Department of Fish and Game, Division of Commercial Fisheries, Fishery Data Series No. 09-72.

Hebert, K. and S. Dressel. 2009 Southeastern Alaska Herring. In Ecosystem Considerations for 2010. North Pacific Fisheries Management Council, p 71-77. Edited by J. Boldt and S. Zador. Joint Institute for the Study of the Atmosphere and Ocean (JISAO) and the School of Aquatic and Fishery Sciences, University of Washington and Alaska Fisheries Science Center, Seattle, WA.

Hedrick, R.P., W.N. Batts, S. Yun, G.S. Traxler, J. Kaufman and J. R.Winton. 2003. Host and geographic range extensions of the North American strain of viral hemorrhagic septicemia virus. Diseases of Aquatic Organisms 55: 211-220.

Hedrick, R.P. 1998. Relationships of the Host, Pathogen, and Environment: Implications for Diseases of Cultured and Wild Fish Populations. Journal of Aquatic Animal Health 10: 107-111.

Hendrix, A.N., J. Straley, C.M. Gabriele and S.M. Gende. 2012. Canadian Journal of Fisheries and Aquatic Science 69: 1783-1797.

Herr, D. and G.R. Galland. 2009. The Ocean and Climate Change: Tools and Guidelines for Action. IUCN, Gland, Switzerland. 72 p.

Hershberger, P.K., N.E. Elder, C.A. Grady, J.L. Gregg, C.A. Pacheco, C. Greene, C. Rice and T.R Meyers. 2009. Prevalence of Viral Erythrocytic Necrosis in Pacific herring and Epizootics in Skagit Bay, Puget Sound, Washington. Journal of Aquatic Animal Health 21: 1-7.

Hershberger, P.K., N.E. Elder, J. Wittouck, K.Stick and R.M. Kocan. 2005. Abnormalities in larvae from the once-largest Pacific herring population in Washington State result primarily from factors independent of spawning location. Transactions of the American Fisheries Society 134: 326-337.

Hershberger, P., J. Gregg, C. Grady, R. Collins and J. Winton. 2010. Kinetics of viral shedding provide insights into the epidemiology of viral hemorrhagic septicemia in Pacific herring. Marine Ecology Progress Series 400:187-193.

Hershberger, PK, J.L. Gregg, C.A. Grady, S.E. LaPatra and J.R. Winton. 2011. Passive immunization of Pacific herring *Clupea pallasii* against viral hemorrhagic septicemia. Journal of Aquatic Animal Health 23: 140-147.

Hershberger, P., Gregg, J., Grady, C., Taylor, L. and J. Winton. 2010a. Chronic and persistent viral hemorrhagic septicemia virus infections in Pacific herring. Diseases of Aquatic Organisms 93:43-49.

Hershberger, P.K., J.L. Gregg, S. Moffitt, R. Brenner, K. Garver, J. Lovy, J.J. Vollenweider and T. Meyers. 2012. Epizootiological observations from five years of Ichthyophonus monitoring in Pacific herring populations. Alaska Marine Science Symposium. Gulf of Alaska – Fish and Fish Habitat.

Hershberger, P.K., J. Gregg, C. Pacheco, J. Winton, J. Richard and G. Traxier. 2007. Larval Pacific herring, *Clupea pallasii* (Valenciennes) are highly susceptible to viral haemorrhagic septicaemia and survivors are partially protected after their metamorphosis to juveniles. Journal of Fish Diseases 30: 445-458.

Hershberger, P., A. Hart, J. Gregg, N. Elder and J. Winton. 2006. Dynamics of viral hemorrhagic septicemia, viral erythrocytic necrosis and ichthyophoniasis in confined juvenile Pacific herring *Clupea pallasii*. Diseases of Aquatic Organisms 70:201-208.

Hershberger, P.K., R.M. Kocan, N.E. Elder, T.R. Meyers and J. Winton. 1999. Epizootiology of viral hemorrhagic septicemia virus in Pacific herring from the spawn-on-kelp fishery in Prince William Sound, Alaska, USA. Diseases of Aquatic Organisms 37:23-31.

Hershberger, P.K., K. Stick, B. Bui, C. Carroll, B. Fall, C. Mork, J.A.Perry, E. Sweeney, J. Wittouck, J. Winton and R. Kocan. 2002. Incidence of *Ichthyophonus hoferi* in Puget Sound fishes and its increase with age of Pacific herring. Journal of Aquatic Animal Health 14: 50-56.

Hewitt, D.A. and J.M. Hoenig. 2005. Comparison of two approaches for estimating natural mortality based on longevity. Fishery Bulletin 103: 433-437.

Hilborn, R. and D. Eggers. 2000. A review of the hatchery programs for pink salmon in Prince William Sound and Kodiak Island, Alaska. Transactions of the American Fisheries Society 129:333-350.

Hollowed, A.B., and W.S. Wooster. 1992. Variability of winter ocean conditions and strong year classes of northeast Pacific groundfish. ICES Marine Science Symposia 195:433–444.

Hollowed, A.B. and W.S. Wooster. 1995. Decadal-scale variations in the eastern subarctic Pacific: II. Response of Northeast Pacific fish stocks. *In* Climate change and northern fish populations, p 373–385. Edited by R.J. Beamish. Canadian Special Publication of Fisheries and Aquatic Sciences 121.

Hollowed, A.B., J.N. Ianelli and P.A. Livingston. 2000. Including predation mortality in stock assessments: a case study for Gulf of Alaska walleye pollock. ICES Journal of Marine Science 57: 279-293.

Holst, J. 1996. Estimating the prevalence of *Ichthyophonus hoferi* (Plehn and Mulsow) in a herring stock (*Clupea harengus L.):* Observed effects of sampling gear, target school density, and migration. Fisheries Research 28: 85-97.

Hourston, A. J. 1978. The decline and recovery of Canada's Pacific herring stocks. Fisheries and Marine Service Technical Report 784. 17p.

Hourston, A. S., 1980. The decline and recovery of Canada's Pacific herring stocks. *In* The Assessment and Management of Pelagic Fish Stocks, p 143-153. Edited by A. Saville. Rapports et Proces-verbaux des Reunions Conseil international Exploration de la Mer (Vol. 177), Conseil International Pour L'exploration de la Mer, Copenhagen.

Hourston, A.S., H. Rosenthal and S. Kerr. 1981. Capacity of juvenile Pacific herring (*Clupea harengus pallasi)* to feed on larvae of their own species. Canadian Technical Report of Fisheries and Aquatic Sciences No. 1044. 9 pp.

Hourston, A.S., and C.W. Haegele. 1980. Herring on Canada’s Pacific coast. Canadian Journal of Fisheries and Aquatic Sciences, Special Publication 48. 23 p.

Hsieh, C.H., A. Yamauchi, T. Nakazawa and W.Wang. 2010. Fishing effects on age and spatial structures undermine population stability of fishes. Aquatic Science 72:165-178.

Hsieh, C.H., S.C.Reiss, R.P. Hewitt and G. Sugihara. 2008. Spatial analysis shows fishing enhances the climatic sensitivity of marine fishes. Canadian Journal of Fisheries and Aquatic Science 65:947-961.

Hsieh, C.H., S.C.Reiss, J.R. Hunter, J.R. Beddington, R.M. May and G. Sugihara. 2006. Fishing elevates variability in the abundance of exploited species. Nature 443:859-862.

Huizer, E.J. 1952. History of the Alaskan herring fishery. Alaska Department of Fisheries Annual Report for 1952, Report 4. 100 p.

Hutchings, J.A. 2000. Collapse and recovery of marine fishes. Nature 406:882-885.

Hutchings, J.A. 2001. Conservation biology of marine fishes: perceptions and caveats regarding assignment of extinction risk. Canadian Journal of Fisheries and Aquatic Sciences 58:108-121.

Hutchings, J.A. 2001a. Influence of population decline, fishing and spawner variability on the recovery of marine fishes. Journal of Fish Biology 59 (Suppl. A):306-322.

Hutchings, J.A. and R.A. Myers. 1993.Effect of age on the seasonality of maturation and spawning of Atlantic cod, *Gadus morhua*, in the Northwest Atlantic. Canadian Journal of Fisheries and Aquatic Science 50: 2468-2474.

Hutchings, J.A., and J.D. Reynolds. 2004. Marine fish population collapses: consequences for recovery and extinction risk. BioScience 54:297-309.

IPCC (Intergovernmental Panel on Climate Change). 2007. Climate Change 2007. *In* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007. Edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller. Cambridge University Press, Cambridge, UK and New York, USA. 996 p.

Ishimatsu A., M. Hayashi, K. Lee, T. Kikkawa and J. Kita. 2005. Physiological effects on fishes in a high-CO_2 world. Journal of Geophysical Research, 110: 8 p.

Ishimatsu, A., T. Kikkawa, M. Hayasji, K. Lee and J. Kita. 2004. Effects of CO_2 on Marine Fish: Larvae and Adults. Journal of Oceanography, 60: 731–741.

Ishimatsu, A. and J. Kita. 1999. Effects of environmental hypercapnia on fish, Japanese Journal of Ichthyology 46: 1–13.

Iverson, S.J., K.J. Frost and S.L.C. Lang. 2002. Fat content and fatty acid composition of forage fish and invertebrates in Prince William Sound, Alaska: factors contributing to among and within species variability. Marine Ecology Progress Series 241: 161-181.

Ivshina, E.R. 2001. Decline of the Sakhalin-Hokkaido herring spawning grounds near the Sakhalin Coast. *In* Herring: Expectations for a new millennium, p 245-254. Edited by F. Funk, J. Blackburn, D. Hay, A.J. Paul, R. Stephenson, R. Torensen, and D. Witherell. University of Alaska Sea Grant, AK-SC-01-04, Fairbanks.

Jackson, J.B., M.X. Kirby, W.H. Berger, K.A. Bjorndal, L.W. Botsford, B.J. Bourque, R.H. Bradbury, R. Cooke, J. Erlandson, J.A. Estes, T.P. Hughes, S. Kidwell, C.B. Lange, H.S. Lenihan, J.M. Pandolfi, C.H. Peterson, R.S. Steneck, M.J. Tegner and R.R. Warner. 2001. Historical overfishing and the recent collapse of coastal ecosystems. Science 293:629-638.

Jakobsson, J. 1985. Monitoring and management of the Northeast Atlantic herring stocks. Canadian Journal of Fisheries and Aquatic Sciences 42:207-221.

Jennings, S. and N.K. Dulvy. 2005. Reference points and reference directions for size-based indicators of community structure. ICES Journal of Marine Science 62:397-404.

Jennings, S., J.D. Reynolds and S.C. Mills. 1998. Life history correlates of responses to fisheries exploitation. Proceedings of the Royal Society, Biological Sciences 265:333-339.

Johnson, L.T., and J.A. Gonzalez. 2005. Nontoxic antifouling? Demonstrating a solution to copper boat bottom paint pollution. In Proceedings of the 14th Biennial Coastal Zone Conference, New Orleans Louisiana. 5 p.

Johnson, S.W, M.L. Murphy, D.J. Csepp, P.M. Harris, and J.F. Thedinga. 2003. A survey of fish assemblages in eelgrass and kelp habitats of southeastern Alaska. NOAA Technical Memorandum NMFS-AFSC-139. 48 p.

Johnson, S.W., A.D. Neff, and J.F. Thedinga. 2005. An atlas on the distribution and habitat of common fishes in shallow nearshore waters of southeastern Alaska. NOAA Technical Memorandum NMFS-AFSC-157. 98 p.

Johnson, S.W., and J.F. Thedinga. 2005. Fish use and size of eelgrass meadows in Southeastern Alaska: A baseline for long-term assessment of biotic change. Northwest Science 79:141–155.

Jones, S.R.M. and S.C. Dawes. 2002. Ichthyophonus hoferi Plehn and Mulsow in British Columbia stocks of Pacific herring, *Clupea pallasi* Valenciennes, and its infectivity to chinook salmon, *Oncorhynchus tshawytscha* (Walbaum). Journal of Fish Diseases 25: 415-421.

JRPT (Joint Northern/Southern Southeast Regional Planning Team). 2004. Comprehensive salmon enhancement plan for Southeast Alaska: Phase III. ADF&G, 291 p.

Kastelein, R.A., S. van der Heul, J. van der Veen, W.C. Verboom, N. Jennings, D. de Haan, and P.J.H. Reijnders. 2007. Effects of acoustic alarms, designed to reduce small cetacean bycatch in gillnet fisheries, on the behavior of North Sea fish species in a large tank. Marine Environmental Research 64:160–180.

Kawasaki, T. 1991. Long-term variability in pelagic fish populations. *In* Proceedings of the International Symposium, Sendai, Japan. 14—18 November, 1989 on Long-Term Variability of Pelagic Fish Populations and their Environment, p 47–60. Edited by T. Kawasaki, S. Tanaka, Y. Toba, and A. Taniguchi. Pergamon Press, Oxford.

Kiefer, D.A., V. Patrick and E. Brown. 2010. An ecosystem model of Prince William Sound herring: a management and restoration tool. Fourth Quarterly Project Report to EVOSTC, Grant FY07:070810.

Kitaysky, A.S., G.L.Hunt, E.N. Flint, M.A. Rubega, and M.B. Decker. 2000. Resource allocation in breeding seabirds: responses to fluctuations in their food supply. Marine Ecology Progress Series 206:283-296.

Kleypas, J.A., R.A. Feely, V.J. Fabry, C. Langdon, C.L. Sabine and L.L. Robbins. 2006. Impacts of ocean Acidification on Coral Reefs and Other Marine Calcifiers: A Guide for Future Research, report of a workshop held 18-20 April 2005, St. Petersburg, FL, sponsored by NSF, NOAA and the U.S. Geological Survey, 88 pp.

Kocan, R., M. Bradley, N. Elder, T. Meyers, W. Batts and J. Winton. 1997. North American Strain of Viral Hemorrhagic Septicemia Virus Is Highly Pathogenic for Laboratory-Reared Pacific Herring. Journal of Aquatic Animal Health 9:279-290.

Kocan, R.M., P. Hershberger, T. Mehl, N. Elder, M. Bradley, D. Wildermuth and K. Stick. 1999. Pathogenicity of *Ichthyophonus hoferi* for laboratory-reared Pacific herring *Clupea pallasii* and its early appearance in wild Puget Sound herring. Diseases of Aquatic Organisms 35:23-29.

Kocan, R.M., P.K. Hershberger. and N.E. Elder. 2001a. Survival of the North American strain of viral hemorrhagic septicemia virus (VHSV) in filtered seawater and seawater containing ovarian fluid, crude oil and serum-enriched culture medium. Diseases of Aquatic Organisms 44:75-78.

Kocan, R.M., P.K. Hershberger, N.E. Elder and J.R. Winton. 2001b. Epidemiology of Viral Hemorrhagic Septicemia among Juvenile Pacific Herring and Pacific Sand Lances in Puget Sound, Washington. Journal of Aquatic Animal Health 13: 77-85.

Kocan, R.M., J.E. Hose, E.D. Brown, and T.T. Baker. 1996b. Pacific herring (*Clupea pallasi*) embryo sensitivity to Prudhoe Bay petroleum hydrocarbons: laboratory evaluation and in situ exposure at oiled and unoiled sites in Prince William Sound. Canadian Journal of Fisheries and Aquatic Sciences 53:2366–2375.

Kocan, R.M., G.D. Marty, M.S. Okihiro, E.D. Brown, and T.T. Baker. 1996a. Reproductive success and histopathology of individual Prince William Sound Pacific herring 3 years after the Exxon Valdez oil spill. Canadian Journal of Fisheries and Aquatic Science 53:2388–2393.

Kreiger, K.J. and B.L. Wing. 1984. Hydroacoustic surveys and identification of humpback whale forage in Glacier Bay, Stephens Passage and Frederick Sound, southeastern Alaska, Summer 1983. NMFS Auke Bay Lab., Juneau, 60 p.

Kreiger, K.J. and B.L. Wing. 1986. Hydroacoustic monitoring of prey to determine humpback whale movements. NOAA Technical Memorandum NMFS F/NWC-66, NMFS Auke Bay Lab., Juneau, 62 pp.

Kritzer, J.P. and P.F. Sale. 2004. Metapopulation ecology in the sea: from Levins' model to marine ecology and fisheries science. Fish and Fisheries 5:131-140.

Kurihara, H., M. Matsui, H. Furukawa, M. Hayashi, and A. Ishimatsu. 2008. Long-term effects of predicted future seawater CO_2 conditions on the survival and growth of marine shrimp *Palaemon pacificus*. Journal of Experimental Marine Biology and Ecology, 367:41–46.

Landingham, J.M., M.V. Sturdevant, M. and R.D. Brodeur. 1998. Feeding habits of juvenile Pacific salmon in marine waters of southeastern Alaska and northern British Columbia. Fishery Bulletin 96:285-302.

Landis, W.G. and P.T. Bryant. 2010. Using weight of evidence characterization and modeling to investigate the cause of the changes in Pacific herring (*Clupea pallasi*) population dynamics in Puget Sound and at Cherry Point, Washington. Risk Analysis 30: 183-202.

Landis, W.G, P.B. Duncan, EH.. Hayes, A.J. Markiewicz, and J.F. Thomas. 2004. A regional retrospective assessment of the potential stressors causing the decline of the Cherry Point Pacific herring run. Human and Ecological Risk Assessment 10:271–297.

Langenbuch, M., C. Bock, D. Leibfritz and H.O. Portner. 2006. Effects of environmental hypercapnia on animal physiology: A 13C NMR study of protein synthesis rates in the marine invertebrate *Sipunculus nudus.* Comparative Biochemistry and Physiology, Part A 144: 479 – 484.

Larson, R., and K. Hebert. 1998. Sitka boat harbor herring spawn deposition study, final report with 1997 and 1998 survey results. ADF&G Report, USFWS COOP-93-0065 number 1448-0007-93-7770. 37 p.

Larson, R., K. Hebert, and M. Pritchett. 2000. Report to the Board of Fisheries, Southeast Alaska-Yakutat Herring Fisheries. Alaska Department of Fish and Game, Division of Commercial Fisheries Regional Information Report No. 1J99-48. 28 p.

Lasker, R. 1985. What limits Clupeoid production? Canadian Journal of Fisheries and Aquatic Sciences 42 (Suppl. 1):31–38.

Lassuy, D. R. 1989. Species profiles. Life histories and environmental requirements of coastal fishes and invertebrates (Pacific Northwest). Pacific herring US Fish Wildl. Serv.Biol. Rep. 82(11.126); US Army Corps of Engineers TR-EL-82-4: 1–18.

Law, R. 2000. Fishing, selection, and phenotypic evolution. ICES Journal of Marine Science 57: 659-669

Lecchini, D., S. Planes and R. Galzin. 2007. The influence of habitat characteristics and conspecifics on attraction and survival of coral reef fish juveniles. Journal of Experimental Marine Biology and Ecology 341:85-90.

Lewis, T.L., D. Esler, and W.S. Boyd. 2007. Foraging behaviors of surf scoters and white-winged scoters during spawning of Pacific herring. The Condor 109:216-222.

Livingstone, P.A. 1993. Importance of predation by groundfish, marine mammals and birds on walleye pollock *Theragra chalcogramma* and Pacific herring *Clupea pallasi* in the eastern Bering Sea. Marine Ecology Progress Series 102:205–215.

Livingston, P.A., A. Ward, G.M. Lang, and M. Yang. 1993. Groundfish food habits and predation on commercially important prey species in the Eastern Bering Sea from 1987 to 1989. NOAA Technical Memorandum NMFS-AFSC-11, 202p.

Logerwell, E.A., and N.B. Hargreaves. 1997. Seabird impacts on forage fish: population and behavioral interactions. *In* Proceedings, Forage Fishes in Marine Ecosystems, p 191–195. AK Sea Grant College Program, AK-SG-97-01:.

Lok, E.K., D. Esler, J.Y. Takekawa, S.W. De La Cruz, W.S. Boyd, D.R. Nysewander, J.R. Evenson, and D.H. Ward. 2011. Stopover habitats of spring migrating surf scoters in Southeast Alaska. Journal of Wildlife Management 75:92-100.

Lok, E.K., M. Kirk, D. Esler, and W.S. Boyd. 2008. Movements of pre-migratory surf and white-winged scoters in response to Pacific herring spawn. Waterbirds 31:385-393.

Longhurst, A. 2002. Murphy's law revisited: longevity as a factor in recruitment to fish populations. Fisheries Research 56: 125 – 131.

Loughlin, T.R., and A.E. York. 2000. An accounting of the sources of Steller sea lion, *Eumetopias jubatus*, mortality. Marine Fisheries Review 62:40–45.

Mace, G.M.and E.J. Hudson. 1999. Attitudes towards sustainability and extinction. Conservation Biology 13:242-246.

MacMillan, J.R. and D. Mulcahy. 1979. Artificial transmission to and susceptibility of Puget Sound fish to viral erythrocytic necrosis (VEN). Journal of the Fisheries Research Board of Canada 36:1097-1101.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society 78:1069–1079.

Mantua, N.J., and S.R. Hare. 2002. The Pacific decadal oscillation. Journal of Oceanography 58:35–44.

Marty, G.D., E.F. Freiberg, T.R. Meyers, J. Wilcock, T.B. Farver and D.E. Hinton. 1998. Viral hemorrhagic septicemia virus, *Ichthyophonus hoferi,* and other causes of morbidity in Pacific herring *Clupea pallasi* spawning in Prince William Sound, Alaska, USA. Diseases of Aquatic Organisms 32:15-40.

Marty, G.D., J.E. Hose, M.D. McGurk, E.D. Brown, and D.E. Hinton. 1997. Histopathology and cytogenetic evaluation of Pacific herring larvae exposed to petroleum hydrocarbons in the laboratory or in Prince William Sound, Alaska, after the Exxon Valdez oil spill. Canadian Journal of Fisheries and Aquatic Sciences 54:1846–1857.

Marty, G.D., P.F. Hulson, S.E. Miller, T.J.Quinn, S.D. Moffitt and R.A. Merizon. 2010. Failure of population recovery in relation to disease in Pacific herring. Diseases of Aquatic Organisms 90:1-14.

Marty, G.D., T.J. Quinn, G. Carpenter, T.R. Meyers and N.H.Willits. 2003. Role of disease in abundance of a Pacific herring (*Clupea pallasi)* population. Canadian Journal of Fisheries and Aquatic Science 60:1258–1265.

Mathiasson, T. 2003. Closing the open sea: development of fishery management in four Icelandic fisheries. Natural Resources Forum 27:1-18.

May, R.M. 1977. Threshholds and breakpoints in ecosystems with a multiplicity of stable states. Nature 269:471–477.

McElhany, P., M.H. Ruckelhaus, M.J. Ford, T.C. Wainwright, and E.P. Bjorkstedt. 2000. Viable salmonid populations and the recovery of evolutionarily significant units. U.S. Dept. of Commerce, NOAA Technical Memorandum NMFS-F/SPO-58. 70 p.

McFarlane, G.A., J.R. King, and R.J. Beamish. 2000. Have there been recent changes in climate? Ask the fish. Progress in Oceanography 47:147–169.

McFarlane, G.A., R.J. Beamish, and J. Schweigert. 2001. Common factors have opposite impacts on Pacific herring in adjacent ecosystems. *In* Herring: Expectations for a new millennium, p 52–68. Edited by F.Funk, J. Blackburn, D. Hay, A. Paul, R. Stephenson, R. Toresen, and D. Witherell. University of Alaska Sea Grant, AK-SG-01-04, Fairbanks.

McGurk, M.D. 1984. Effects of delayed feeding and temperature on the age of irreversible starvation and on the rates of growth and mortality of Pacific herring larvae. Marine Biology 84:13–26.

McGurk, M.D. 1989. Advection, diffusion and mortality of Pacific herring larvae *Clupea harengus pallasi* in Bamfield Inlet, British Columbia. Marine Ecology Progress Series 51:1–18.

McGurk, M.D., and E.D. Brown. 1996. Egg-larval mortality of Pacific herring in Prince William Sound, Alaska, after the Exxon Valdez oil spill. Canadian Journal of Fisheries and Aquatic Sciences 53:2343–2354.

McKinnell, S.M., R.D. Brodeur, R., K. Hanawa, A.B. Hollowed, J.J. Polovina and C.I. Zhang. 2001. An introduction to the beyond El Nino conference: climate variability and marine ecosystem impacts from the tropics to the Arctic. Progress in Oceanography, 49: 1-6.

McQuinn, I.H. 1997. Metapopulations and the Atlantic herring. Reviews in Fish Biology and Fisheries 7:297-329.

MEA (Millenium Ecosystem Assessment). 2005. Living beyond our means; natural assets and human well-being: synthesis. World Resources Institute, Washington DC: 16.

Mecklenburg, C. W., T. A. Mecklenburg and L. K. Thorsteinson 2002. Fishes of Alaska. Am Fish Soc: 1-134.

Mellergaard, S. and B. Spanggaard. 1997. An *Ichthyophonus hoferi* epizootic in herring in the North Sea, the Skagerrak, the Kattegat and the Baltic Sea. Diseases of Aquatic Organisms 28:191-199.

Melvin, G.D. and R.L. Stephenson. 2007. The dynamics of a recovering fish stock: Georges Bank herring. ICES Journal of Marine Science 64: 69-82.

Merrick, R. L., 1997. Current and historical roles of apex predators in the Bering Sea ecosystem. Journal of Northwest Atlantic Fishery Science, 22:343-356.

Mertz, G., and R.A. Myers. 1996. Influence of fecundity on recruitment variability of marine fish. Canadian Journal of Fisheries and Aquatic Sciences 53:1618-1625.

Meyers, T.R., A.K. Hauck, W.D. Blankenbeckler and T. Minicucci. 1986. First report of viral erythrocytic necrosis in Alaska, USA, associated with epizootic mortality in Pacific herring, *Clupea harengus pallasi* (Valenciennes). Journal of Fish Diseases 9:479-491.

Meyers, T.R., S. Short and K. Lipson. 1999. Isolation of the North American strain of viral hemorrhagic septicemia virus (VHSV) associated with epizootic mortality in two new host species of Alaskan marine fish. Diseases of Aquatic Organisms 38:81-86.

Meyers, T.R., S. Short, K. Lipson, W.N. Batts, J.R. Winton, J. Wilcock and E. Brown. 1994. Association of viral hemorrhagic septicemia with epizootic hemorrhages of the skin in Pacific herring *Clupea pallasi* from Prince William Sound and Kodiak Island, Alaska, USA. Diseases of Aquatic Organisms 19:27-37.

Meyers, T. and J. Winton. 1995. Viral hemorrhagic septicemia virus in North America. Annual Review of Fish Diseases 5:3-24.

Miller, A.J. and N. Schneider. 2000. Interdecadal climate regime dynamics in the North Pacific Ocean: theories, observations and ecosystem impacts. Progress in Oceanography 47: 355-379.

Minchinton, T.E. 1997. Life on the edge: conspecific attraction and recruitment of populations to disturbed habitats. Oecologia 111:45 – 52.

Misund, O.A., J.T. Ovredal, and M.T. Hafsteinsson. 1996. Reactions of herring schools to the sound field of a survey vessel. Aquatic Living Resources 9:5–11.

Mitson, R.B. 1995. Underwater noise of research vessels review and recommendations. ICES Cooperative Research Report No. 209, Copenhagen Denmark. 61 p.

Mitson, R.B., and H.P. Knudsen. 2003. Causes and effects of underwater noise on fish abundance estimation. Aquatic Living Resources 16:255–263.

Mobley, C. 1996. Cultural resource investigations at Auke Bay, Juneau, Alaska. NMFS Report. Charles M. Mobley and Associates, Anchorage Alaska. 96 p.

Moores, J.A. and G.H. Winters. 1982. Growth patterns in a Newfoundland Atlantic herring (*Clupea harengus harengus*) stock. Canadian Journal of Fisheries and Aquatic Science 39: 1353-1371.

Morissette, L., V. Christensen and D. Pauly. 2012. Marine mammal impacts in exploited ecosystems: would large scale culling benefit fisheries? PLOS ONE 7(9). 18 ppl.

Morris, J.A., M.R. Carman, K.E. Hoagland, E.R. Green-Beach, and R.C. Karney. 2009. Impact of the invasive colonial tunicate *Didemnum vexillum* on the recruitment of the bay scallop (*Argopecten irradians irradians*) and implications for recruitment of the sea scallop (*Placopecten magellanicus*) on Georges Bank. Aquatic Invasions 4:207–211.

Motoda, S. and Y. Hirano.1 963. Review of Japanese herring investigations.Rapp. Pa-V. Reun. Cons. Int. Explor. Mer 154: 249-261.

Moustahfid, H., J.S. Link, W.J. Overholtz, and M.C. Tyrell. 2009. The advantage of explicitly incorporating predation mortality into age-structured stock assessment models: an application for Atlantic mackerel. ICES Journal of Marine Science 66 (3): 445-454.

Mueter, F.J., J.L. Boldt, B.A. Megrey and R.M. Peterman. 2007. Recruitment and survival of Northeast Pacific Ocean fish stocks: temporal trends, covariation, and regime shifts. Canadian Journal of Fisheries and Aquatic Sciences, 64: 911-927.

Munro, J.A., and W.A. Clemens. 1931. Water fowl in relation to the spawning of herring in British Columbia. Biological Board of Canada Bulletin 17:1-46.

Murphy, M.L., S.W. Johnson and D.J. Csepp. 2000. A Comparison of Fish Assemblages in Eelgrass and Adjacent Subtidal Habitats Near Craig, Alaska. Alaska Fishery Research Bulletin 7:11-21.

Murphy, R.R., D.W. Willis, and T.A. Springer. 1991. The relative weight index in fisheries management: status and needs. Fisheries 16(2):30–38.

Musick, J.A. 1998. Endangered marine fishes: criteria and identification of North American stocks at risk. Fisheries 23:28-30.

Musick, J.A. 1999. Criteria to define extinction risk in marine fishes. Fisheries 24:6-14.

Musick, J.A., M.M. Harbin, S.A. Berkeley, G.H. Burgess, A.M. Eklund, L. Findley, R.G. Gilmore, J.T. Golden, D.S. Ha, G.R. Huntsman, J.C. McGovern, S.J. Parker, S.G. Poss, E. Sala, T.W. Schmidt, G.R. Sedberry, H. Weeks, and S.G. Wright. 2000. Marine, estuarine, and diadromous fish stocks at risk of extinction in North America (exclusive of Pacific salmonids). Fisheries 25:6–24.

Myers, R. A. 2008. Recruitment: Understanding Density-Dependence in Fish Populations. *In* Handbook of Fish Biology and Fisheries, Volume 1: Fish Biology, p 123-148. Edited by P. J. Hart and J. D. Reynolds. Blackwell Publishing Ltd, Oxford, UK.

Myers, R. A. and N.J. Barrowman. 1996. Is fish recruitment related to spawner abundance? Fishery Bulletin 94: 707-724.

Myers, R.A., N.J. Barrowman, .J.A. Hutchings and A.A. Rosenberg. 1995. Population dynamics of exploited fish stocks at low population levels. Science 269:1106-1108

Myers, R.A., K.G. Bowen, and N.J. Barrowman. 1999. Maximum reproductive rate of fish at low population sizes. Canadian Journal of Fisheries and Aquatic Sciences 56:2404-2419.

Nagasawa, K. 2001. Long-term variations in abundance of Pacific herring (*Clupea pallasii*) in Hokkaido and Sakhalin related to changes in environmental conditions. Progress in Oceanography 49:551–564.

Nammack, M., L. Manning, A. Mullan, and S. Rumsey. 2013. NMFS Guidance on Conducting Statue Reviews under the Endangered Species Act. http://www.nmfs.noaa.gov/pr/listing/conducting_a_status_review_under_the_esa_-_guidance.pdf. (Accessed 10/23/2013).

Nash, R.D.M., A.H. Valencia, and A.J. Geffen. 2006. The origin of Fulton’s condition factor – setting the record straight. Fisheries 31:236-238.

Nevill, J. 2009. Overfishing, uncertainty, and ocean governance: Lord Perry’s question revisited. PhD thesis, University of Tasmania, Australia. 441 pp.

Nicholson, M.D. and S. Jennings. 2004. Testing candidate indicators to support ecosystem-based management: the power of monitoring surveys to monitor trends in fish community metrics. ICES Journal of Marine Science 61: 35-42.

NMFS (National Marine Fisheries Service). 1993. Defining overfishing-defining stock rebuilding. NOAA Tech. memo. NMFS-F/SPO-8. Rosenberg, A.A (Ed). 70p.

NMFS (National Marine Fisheries Service). 2009. Aerial survey of Steller sea lions in Alaska , June-July 2009 and update on the status of the western stock in Alaska. NOAA Memorandum. 8 p.

NMFS (National Marine Fisheries Service). 2009a. Our living oceans. Report on the status of U.S. living marine resources, 6th edition. U.S. Department of Commerce. NOAA Technical Memorandum. NMFS-F/SPO-80, 369 p.

Norcross, B.L., and E.D. Brown. 2001. Estimation of first-year survival of Pacific herring from a review of recent stage-specific studies. Pages 535–558 in F. Funk, J. Blackburn, D. Hay, A.J. Paul, R. Stephenson, R. Toresen, and D. Witherell (eds.). Herring: Expectations for a new millenium. Alaska Sea Grant College Program, AK-SG-01-04.

Norcross, B.L., J.E. Hose, M. Frandsen, and E.D. Brown. 1996. Distribution, abundance, morphological condition, and cytogenetic abnormalities of larval herring in Prince William Sound, Alaska, following the Exxon Valdez oil spill. Canadian Journal of Fisheries and Aquatic Sciences 53:2376–2387.

NRC (National Resource Council). 1998. Improving fish stock assessments. National Academy Press, Washington, DC.

Nuka.2012.Southeast Alaska Vessel Traffic Study. Nuka Research and Planning Group, LLC. Seldovia, AK. 120 pp.

Ojaveer, E. 2006. On the external and parental effects in the early development of herring (*Clupea pallasi*) at the NE Kamchatka. Fishery Research 81: 1-8.

Okkonen, S.R., T.J. Weingartner, S.L. Danielson, D.L. Musgrave, and G.M. Schmidt. 2003. Satellite and hydrographic observations of eddy-induced shelf-slope exchange in the northwestern Gulf of Alaska. Journal of Geophysical. Research 108:3033.

Olsen E.M., M. Heino, G.R. Lilly, M.J. Morgan, J. Brattey, B. Ernande and U. Dieckmann. 2004. Maturation trends indicative of rapid evolution preceded the collapse of northern cod. Nature 428: 932-935.

Orr, J.C., V.J. Fabry, O. Aumont, L. Bopp, S.C. Doney, R.A. Feely, A. Gnanadesikan, N. Gruber, A. Ishida, F. Joos, R.M. Key, K. Lindsay, E. Maier-Reimer, R. Matear, P. Monfray, A. Mouchet, R.G. Najjar, G. Plattner, K.B. Rodgers, C.L. Sabine, J.L. Sarmiento, R. Schitzer, R.D. Slater, I.J. Totterdall, M. Weirig, Y. Yamanaka and A. Yool. 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. Nature, 437: 681-685.

Orsi, J.A., A.C. Wertheimer, M.V. Sturdevant, E.A.Fergusson, D.G.Mortensen and B.L. Wing. 2004. Juvenile chum salmon consumption of zooplankton in marine waters of southeastern Alaska: a bioenergetics approach to implications of hatchery stock interactions. Reviews in Fish Biology and Fisheries 14:335-359.

Outram, D. N. 1955. The development of the Pacific herring egg and its use in estimating age of spawn. Fish Res Bd Can Pacific Biological Station (Circular 40): 9.

Outram, D.N. 1958. The magnitude of herring spawn losses due to bird predation on the west coast of Vancouver Island. Fisheries Research Board of Canada, Pacific Biological Station Progress Rep. 111:9-13.

Overholtz, W.J., L.D. Jacobsen and J.S. Link. 2008. An ecosystem approach for assessment advice and biological reference points for the Gulf of Maine-Georges Bank Atlantic herring complex. North American Journal of Fisheries Management 28: 247-257.

Overholtz, W.J. and J.S. Link. 2007. Consumption impacts by marine mammals, fish and seabirds on the Gulf of Maine-Georges Bank Atlantic herring (*Clupea harengus*) complex during the years 1977-2002. ICES Journal of Marine Science 64:83–96.

Overholtz, W.J., J.S. Link, and L.E. Suslowicz. 2000. Consumption of important pelagic fish and squid by predatory fish in the northeastern USA shelf ecosystem with some fishery comparisons. ICES Journal of Marine Science 57:1147-1159.

Pallson, W.A. 1984. Egg mortality upon natural and artificial substrata within Washington State spawning grounds of Pacific herring (*Clupea harengus pallasi*). M.S. thesis. University of Washington, Seattle: 191 p.

Parks, R., M. Donnier-Marechal, P.E. Frickers, A. Turner, and J.W. Readman. 2010. Antifouling biocides in discarded marine paint particles. Marine Pollution Bulletin 60:1226–1230.

Patterson, K.R. 1996. Modelling the impact of disease-induced maortality in an exploited population: the outbreak of the fungal parasite *Ichthyophonus hoferi* in the North Sea herring (*Clupea harengus*). Canadian Journal of Fisheries and Aquatic Sciences 53:2870 -2887.

Patterson, K. 1997. Fisheries for small pelagic species:an empirical approach to management targets. Reviews in Fish Biology and Fisheries 2:321-338.

Paul, A.J., and J.M. Paul. 1998. Spring and summer whole-body energy content of Alaskan juvenile Pacific herring. Alaska Fishery Research Bulletin 5:131–136.

Pauly, D. 1995. Anecdotes and the shifting baseline syndrome of fisheries. Tree 10(10): 430.

Pauly, D., V. Christensen, S. Guenette, T.J. Pitcher, R. Sumaila, C.J. Walters, R. Watson and D. Zeller. 2002. Towards sustainability in world fisheries. Nature 418: 689-695.

Payne, P.M., D.N. Wiley, S.B. Young, S. Pittman, P.J. Clapham, P., and J.W. Jossi. 1990. Recent fluctuations in the abundance of baleen whales in the southern Gulf of Maine in relation to changes in selected prey. Fishery Bulletin 88:687–696.

Pearson, W.H., R.A. Elston, R.W. Bienert, A.S. Drum and L.D. Antrim. 1999. Why did the Prince William Sound, Alaska , Pacific herring (*Clupea pallasi*) collapse in 1993 and 1994? Review of hypotheses. Canadian Journal of Fisheries and Aquatic Sciences 56:711-737.

Perry, R.I., P. Cury, K. Brander, S. Jennings, C. Mollmann and B. Planque. 2010. Sensitivity of marine systems to climate and fishing: Concepts, issues and management responses. Journal of Marine Systems 79: 427-435.

Perry, R.I., and J.F. Schweigert. 2008. Primary productivity and the carrying capacity for herring in NE Pacific marine ecosystems. Progress in Oceanography 77:241–251.

Peterson, C.H., S.D. Rice, J.W. Short, D. Esler, J.L. Bodkin, B.E. Ballachey, and D.B. Irons. 2003. Long-term ecosystem response to the Exxon Valdez oil spill. Science 302:2082–2086.

Petitgas, P., D. Reid, B. Planque, E. Noguiera, B. O'Hea and U. Cotano. 2006. The entrainment hypothesis: an explanation for the persistence and innovation in spawning migrations and life cycle spatial patterns. ICES CM2006/B:07

Piatt, J.F., K.J. Kuletz, A.E. Burger, S.A. Hatch, V.L. Friesen, T.P. Birt, M.L. Arimitsu, G.S. Drew, A.M.A. Harding and K.S. Bixler. 2007. Status Review of the Marbled Murrelet (*Brachyramphus marmoratus*) in Alaska and British Columbia. U.S. Geological Survey Open-File Report 2006-1387, 258 p.

Piatt, J.F., and D.A. Methven. 1992. Threshold foraging behavior of baleen whales. Marine Ecology Progress Series 84:205–210.

PICES (North Pacific Marine Science Organization). 2001. An introduction to the beyond El Niño conference: climate variability and marine ecosystem impacts from the tropics to the Arctic. Progress in Oceanography 49:1–6.

Pikitch, E., Boersma, P.D., Boyd, I.L., Conover, D.O., Cury, P., Essington, T., Heppell, S.S., Houde, E.D., Mangel, M., Pauly, D., Plagányi, É., Sainsbury, K., and Steneck, R.S. 2012. Little Fish, Big Impact: Managing a Crucial Link in Ocean Food Webs. Lenfest Ocean Program. Washington, DC. 108 pp.

Pinsky, M.L., O.P. Jensen, D. Ricard and S.R. Palumbi. 2011. Unexpected patterns of fisheries collapse in the world's oceans. Proceedings of the National Academy of Science 108 (20):8317-8322.

Pitcher, K.W., P.F. Olesiuk, R.F. Brown, M.S. Lowry, S.J. Jeffreies. J.L. Sease, W.L. Perrymen, C.E. Stinchcomb, and L.F. Lowry. 2007. Abundance and distribution of the eastern North Pacific Steller sea lion (*Eumetopias jubatus*) population. Fishery Bulletin 107:102–115.

Polovina, J.J. 2005. Climate variation, regime shifts, and implications for sustainable fisheries. Bulletin of Marine Science 76:233–244.

Popper, A.N. 2003. Effects of Anthropogenic Sounds on Fishes. Fisheries 28(10):24-31.

Powles, H., M.J. Bradford, R.G. Bradford, W.G. Doubleday, S. Innes, and C.D. Levings. 2000. Assessing and protecting marine species. ICES Journal of Marine Science 57:669-676.

Pritchett, M. 2005. 2006 Report to the Alaska Board of Fisheries: Southeast Alaska-Yakutat Herring Fisheries. Alaska Department of Fish and Game Fishery Management Report No. 05-67. 25 pp.

Pritchett, M. 2007. Project Operational Plan for the 2007 Southeast Alaska herring Stock Assessment. Alaska Department of Fish and Game Regional Information Report No. 1J07-15.

Pritchett, M.,S. Dressel, and K. Monagle. 2007. Berners Bay herring research for 2005 and 2006. ADF&G Regional Information Report No. 1J07-01. 13 p.

Pritchett, M. and K. Hebert. December 2008. 2009 report to the Alaska Board of Fisheries: Southeast Alaska – Yakutat Herring Fisheries. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report No. 08-65. 25 pp.

Pryor, F., B. Lynch, and P. Skannes. 2009. 2005 Annex: Chinook salmon plan for Southeast Alaska. Alaska Department of Fish and Game, Fishery Management Report No. 09-29, Anchorage.

Purcell, J.E. 1989. Predation on fish larvae and eggs by the hydromedusa *Aequorea victoria* at a herring spawning ground in British Columbia. Canadian Journal of Fisheries and Aquatic Science 46:1415-1427.

Purcell, J.E. and J.J. Grover. 1990. Predation and food limitation as causes of mortality in larval herring at a spawning ground in British Columbia. Marine Ecology Progress Series 59:55–61.

Purcell, J.E. and M.V. Sturdevant. 2001. Prey selection and dietary overlap among zooplanktiverous jellyfish and juvenile fishes in Prince William Sound, Alaska. Marine Ecology Progress Series 210:67-83.

Purvis, A., J. L. Gittleman, G. Cowlishaw and G.M. Mace. 2000. Predicitng extinction risk in declining species. Proceedings of the Royal Society, B 267:1947-1952.

Quinn, T.J., R. Fagen and J.Zheng. 1990. Threshold management policies for exploited populations. Canadian Journal of Fisheries and Aquatic Sciences 47:2016-2029.

Quinn, T.J., G.D. Marty, J. Wilcock and M. Willette. 2001. Disease and Population assessment of Pacific Herring in Prince William Sound, Alaska. *In* Herring: Expectations for a New Millenium, p 363-378. Edited by F. Funk, J. Blackburn, D. Hay, A.J. Paul, R. Stephenson, R. Toresen and D. Witherell. AK Sea Grant College Program, AK-SG-01-04:363-378

Reed, R.K., and J.D. Schumacher. 1986. Physical Oceanography. *In* The Gulf of Alaska: physical environment and biological resources, p 57–75. Edited by D.W. Hood, and S.T. Zimmerman. Ocean Assessment Division, NOAA.

Reeves, P.A., B.S. Stewart, P.J. Clapham and J.A. Powell. 2002. A Guide to Marine Mammals of the World. Alfred A. Knopf Publ., New York. 526 pp.

Reid, G.M. 1971. Age composition, weight, length, and sex of herring, *Clupea pallasii*, used for reduction in Alaska, 1929-66. NOAA Technical Report NMFS SSRF 634. 25 p.

Reid, G.M. 1972. Alaska's Fishery Resources…the Pacific Herring. Fishery Facts-2. US Department of Commerce NMFS Extension Publication, Seattle WA June 1972. 20 p.

Ressler, P.H., J.A. Holmes, G.W. Fleischer, R.E. Thomas, and K.C. Cooke. 2007. Pacific hake, *Merluccius productus*, autecology: a timely review. Marine Fisheries Review 69:1-24.

Reynolds, J.D., N.K. Dulvy, N.B. Goodwin, and J.A. Hutchings. 2005. Biology of extinction risk in marine fishes. Proceedings of the Royal Society, Biological Sciences 272:2337-2344.

Reynolds, J.D. and S. Jennings. 2000. The role of animal behavior in marine conservation. In: Behavior and Conservation, p 238-257. Edited by L.M. Gosling and W.J. Sutherland. Cambridge University Press, Cambridge.

Rice, D.W., 1978. The humpback whale in the North Pacific: distribution, exploitation and numbers. *In* Appendix 4: Report on a workshop on problems related to humpback whales (*Megaptera novaeangliae*) in Hawaii, p. 29-44. Edited by K.S. Norris and R.R. Reeves. US Department of Commerce., Nat. Tech. Info. Serv. PB-280 794, Springfield VA.

Rice, D.W., and F.L. Harrison. 1978. Copper sensitivity of Pacific herring, *Clupea harengus pallasi*, during its early life history. Fishery Bulletin 76:347–356.

Rice, S.D., J.R. Moran, J.M. Straley, K.M. Boswell, and R.A. Heintz. 2011. Significance of whale predation on natural mortality rate of Pacific herring in Prince William Sound. Exxon Valdez Oil Spill, Restoration Project 100804 Final Report.

Richardson, A.J., A. Bakun, G.C. Hays and M.J. Gibbons. 2009. The jellyfish joyride: causes, consequences and management responses to a more gelatinous future. Trends in Ecology and Evolution 24(6):312-322.

Ricker, W.E. 1975. Computation and interpretation of biological statistics of fish populations. Bulletin of the Fisheries Research Board of Canada 191. 382 p.

Rickman, S.J., N.K. Dulvy, S. Jenning, and J.D. Reynolds. 2000. Recruitment variation related to fecundity in marine fishes. Canadian Journal of Fisheries and Aquatic Sciences 57:116-124.

Riebesell, U. 2004. Effects of CO_2 enrichment on marine phytoplankton. Journal of Oceanography 60: 719-729.

Riebesell, U., I. Zondervan, B. Rost, P.D. Tortell, R.E. Zeebe and F.M.M. Morel. 2000. Reduced calcification of marine plankton in response to increased atmospheric CO_2. Nature 407: 364-367.

Roberts, C.M., and J.P. Hawkins. 1999. Extinction risk in the sea. Trends in Ecology & Evolution 14:241-246.

Rodway, M. S., H.M. Regehr, J. Ashley, P.V. Clarkson, R.I. Goudie, D.E. Hay, C.M. Smith, and K. G. Wright. 2003. Aggregative response of harlequin ducks to herring spawning in the Strait of Georgia, British Columbia. Canadian Journal of Zoology 81:504–514.

Rogers, S.H. 1965. Herring fishery in southeastern Alaska. U.S. Department of the Interior, Fish and Wildlife Service, Commercial Fisheries Review 27 (8). 6 p.

Rooper, C.N. and L.J. Haldorson. 2000. Consumption of Pacific herring (*Clupea pallasi*) eggs by greenling (Hexagrammidae) in Prince William Sound, Alaska. Fisheries Bulletin 98:655-659.

Rooper, C., Haldorsen, L. and T. Quinn. 1998. An Egg-Loss Correction for Estimating Spawning Biomass of Pacific Herring in Prince William Sound, Alaska. Alaska Fishery Research Bulletin 5(2): 137-142.

Rooper, C.N., L.J. Haldorson, and T.J. Quinn. 1999. Habitat factors controlling Pacific herring (*Clupea pallasi*) egg loss in Prince William Sound, Alaska. Canadian Journal of Fisheries and Aquatic Sciences 56:1133–1142.

Rose, K.A., B.A. Megrey, D. Hay, F. Werner and J. Schweigert. 2008. Climate regime effects on Pacific Herring growth using coupled nutrient-phytoplankton-zooplankton and bioenergetics models. Transactions of the American Fisheries Society 137: 278-297.

Rosenberg, A.A. 1993. Defining Overfishing – Defining Stock Rebuilding. NOAA Technical Memorandum.

Rosenberg, A.A. 2003. Managing to the margins: the overexploitation of fisheries. Frontiers in Ecology and the Environment 1:102-106.

Rosenberg, A.A. 2009. Precautionary management reference points and management strategies. FAO Precautionary approach to fishing – Part 2: Scientific papers. http://www.fao.org/docrep/003/W1238E06.htm12 p.

Rosenberg, A.A. and V.R. Restrepo. 1994. Uncertainty and risk evaluation in stock assessment advice for U.S. marine fisheries. Canadian Journal of Fisheries and Aquatic Sciences 51:2715-2720.

Rosier, C., J. Parker, L. Simpson and J. Valentine. 1967a. Report, Herring Spawn Fishery, 1966. 28 p.

Rosier, C., J. Parker, L. Simpson and J. Valentine. 1967b. Report, Herring Spawn Fishery, 1967. 31 p.

Rosier, C.,J. Parker, J. Valentine and D. Daisy.1968. Report, Herring Spawn Fishery, 1968. 29 p.

Rosier, C., L. Simpson and J. Valentine. 1964. Herring Spawn Fishery, 1959 - 1964. Ketchikan Management, ADF&G, Commercial Fisheries Division. 13 p.

Rosier, C., L. Simpson and J. Valentine. 1965. Herring Spawn Fishery 1959-1965. ADF&G, Ketchikan, AK.

Rounsefell, G.A. 1930. Contribution to the biology of Pacific herring, *Clupea pallasii*, and the condition of the fishery in Alaska. Bulletin of the U.S. Bureau of Commercial Fisheries 45:227-320.

Rounsefell, G.A., and E.H. Dahlgren. 1935. Races of herring, *Clupea pallasii*, in Southeastern Alaska. Bulletin of the Bureau of Fisheries 48:119–141.

Royal Society, The. 2005. Ocean acidification due to increasing atmospheric carbon dioxide. The Royal Society Policy Document 12/05, 60 p.

Royer, T.C. and C.E. Grosch. 2007. Update of freshwater discharge model for Gulf of Alaska. North Pacific Research Board Project Final Report 734, 12 p

Sadovy, Y. 2001. The threat of fishing to highly fecund fish. Journal of Fish Biology 59:90-108.

Sayer, A.M., and D.D. Holum. 2008. The Southeast Alaska Southern Southeast Inside sablefish fishery information report, with outlook to the 2008 Fishery. Alaska Department of Fish and Game, Fishery Management Report No. 08-44, Anchorage. 43 p.

Schwarz, A.L., and G.L. Greer. 1984. Responses of Pacific herring, *Clupea harengus pallasi*, to some underwater sounds. Canadian Journal of Fisheries and Aquatic Sciences 41:1183–1192.

Schweigert, J.F. 1995. Environmental effects on long-term population dynamics and recruitment to Pacific herring (*Clupea pallasi*) populations in southern British Columbia. Canadian Special Publication Fisheries and Aquatic Science, 121:569-582.

Schweigert, J.F. 2004. Stock assessment for British Columbia herring in 2004 and forecasts of the potential catch in 2005. Fisheries and Oceans Canada Research Document 2004/081. 95 p.

Schweigert, J.F., J.L. Boldt, L. Florstrand and J.S. Cleary. 2010. A review of factors limiting recovery of Pacific herring stocks in Canada. ICES Journal of Marine Science 67:1903 - 1913.

Schweigert, J.F., C. Fu, C.C. Wood and T.W. Therriault. 2007. A risk assessment framework for Pacific herring stocks in British Columbia. CSAS Research Document 2007/047. Fisheries and Oceans Canada, Nanaimo BC. 74 p.

Schweigert, J., F. Funk, K. Oda, and T. Moore. 2002. Herring size-at-age variation in the North Pacific. *In* PICES-GLOBEC International Program on Climate Change and Carrying Capacity: Report of the 2001 BASS/MODEL, MONITOR and REX Workshops, and the 2002 MODEL/REX Workshop, p. 44 – 47. Edited by H.P. Batchelder, G.A. McFarlane, B.A., Megrey, D.L. Mackas, and W.T. Peterson. PICES Sci. Rep. No. 20.

Scott, B., G. Marteinsdottir and P. Wright. 1999. Potential effects of maternal factors on spawning stock-recruitment relationships under varying fishing pressure. Canadian Journal of Fisheries and Aquatic Science 56: 1882-1890.

SDJV (Sea Duck Joint Venture Management Board). 2008. Sea Duck Joint Venture Strategic Plan 2008 – 2012. USFWS, Anchorage, Alaska; CWS, Sackville, New Brunswick. 95 pp.

Sealy, S.G. 1975. Aspects of the breeding biology of marbled murrelets in British Columbia. Bird Banding 46:141-154.

Sewall, F., Heintz, R. and M. Carls. 2009. Effects of Reduced Ph on Embryonic Pacific Herring Development: Implications for Ocean Acidification Impacts on Marine Fish. Poster: Gulf of Alaska – Fish and Fish Habitat, Alaska Marine Science Symposium, Jan. 2009.

Sharpe, Fred A. 2001. Social foraging of the Southeast Alaskan humpback whale, *Megaptera novaeangliae*. PhD thesis, Simon Frazer University, British Columbia, Canada.

Sharpe, F.A. and L.M. Dill. 1997. The behavior of Pacific herring schools in response to artificial humpback whale bubbles. Canadian Journal of Zoology 75:725-730.

Shertzer, K.W., M.H. Prager, D.S.Vaughan and E.H.Williams. 2008. Fishery models. *In* Population dynamics. Encyclopedia of Ecology. Vol. 2 of 5, p. 1582–1593. Edited by S.E. Jorgensen and B. Fath. Elsevier, Oxford.

Shin, Y., M. Rochet, S. Jennings, J.G. Field and H. Gislason. 2005. Using size-based indicators to evaluate the ecosystem effects of fishing. ICES Journal of Marine Science, 62: 384-396.

Shirayama, Y. and H. Thornton. 2005. Effect of increased atmospheric CO_2 on shallow water marine benthos. Journal of Geophysical Research, 110: 7 p

Short, J.W., S.D. Rice, R.A. Heintz, M.G. Carls, and A. Moles. 2003. Long-term effects of crude oil on developing fish: lessons from the Exxon Valdez oil spill. Energy Sources 25:509–517.

Shuter, B.J. and P.A. Abrams. 2005. Introducing the symposium “Building on Beverton’s legacy: life history variation and fisheries management”. Canadian Journal of Fisheries and Aquatic Science 62:725-729.

Sigler, M.F., and D.J. Csepp. 2007. Seasonal abundance of two important forage species in the North Pacific Ocean, Pacific herring and walleye pollock. Fisheries Research 83:319–331.

Sigler, M.F., D.J. Tollit, J.J. Vollenweider, J.F. Thedinga, D.J. Csepp, J.N. Womble, M.A. Wong, M.J. Rehberg, and A.W. Trites. 2009. Steller sea lion foraging response to seasonal changes in prey availability. Marine Ecology Progress Series 388:243–261.

Sigler, M.F., J.N.Womble, and J.J. Vollenweider. 2004. Availability to Steller sea lions (*Eumetopias jubatus*) of a seasonal prey resource: a prespawning aggregation of eulachon (*Thaleichthys pacificus*). Canadian Journal of Fisheries and Aquatic Science 61:1475-1484.

Simila, T., Holst, J.C. and I. Christensen. 1996. Occurrence and diet of killer whales in northern Norway: seasonal patterns relative to the distribution and abundance of Norwegian spring-spawning herring. Canadian Journal of Fisheries and Aquatic Science 53:769-779.

Sims, D.W. and A. Southward. 2006. Dwindling fish numbers already of concern in 1883. Nature 439:660.

Simmonds, E.J. 2007. Comparison of two periods of North Sea herring stock management: success, failure and monetary value. ICES Journal of Marine Science 64:686–692.

Sissenwine, M. P., E. B. Cohen, and M. D.Grosslein. 1984. Structure of the Georges Bank ecosystem. Rapp. P.-v. Reun. Cons. Int. Explor. Mer 183:243-254.

Skaret, G., B.E. Axelsen, L. Nøttestad, A. Fernö, and A. Johannessen. 2002. Brief Communication: Herring as cannibals. Journal of Fish Biology 61:1050-1052.

Skud, B.E.1959. Herring spawning surveys in southeastern Alaska. U.S. Fish and Wildlife Service Special Scientific Report, Fisheries No. 321. 20 p.

Skud, B.E., H.M. Sakuda and G.M. Reid. 1960. Statistics of the Alaska herring fishery 1878-1956. Fish and Wildlife Service Statistical Digest 48, Washington. 21 p.

Skud, B.E. 1963. Herring tagging experiments in southeastern Alaska. Fishery Bulletin 63: 19-32.

Smith, A.T. and M.M. Peacock. 1990. Conspecific Attraction and the Determination of Metapopulation Colonization Rates. Conservation Biology 4: 320-322.

Speckman S.G., J.F. Piatt, and A.M. Springer. 2003. Deciphering the social structure of marbled murrelets from behavioral observations at sea. Waterbirds:266–274.

Spratt, J.D. 1981. Status of the Pacific herring, *Clupea harengus pallasi*, resource in California 1972 to 1980. California Department of Fish and Game, Fishery Bulletin 171. 107 p.

Springer, A.M., J.A. Estes, G.B. van Vliet, T.M. Williams, D.F. Doak, E.M. Danner, K.A. Forney and B. Pfister. 2003. Sequential megafaunal collapse in the North Pacific Ocean: An on-going legacy of industrial whaling? PNAS, 100: 12223–12228.

Stabeno, P.J., N.A. Bond, A.J. Hermann, N.B. Kachel, C.W. Mordy, and J.E. Overland. 2004. Meteorology and oceanography of the Northern Gulf of Alaska. Continental Shelf Research 24:859–897.

Stamps, J.A., 1988. Conspecific Attraction and Aggregation in Territorial Species. The American Naturalist 131(3): 329-247.

Straley, J.M. 1994. Seasonal characteristics of humpback whales (*Megaptera novaeangliae*) in southeastern Alaska. Master's thesis, University of Alaska, Fairbanks, Alaska.

Steele, J. 1996. Regime shifts in fisheries management. Fisheries Research 25:19–23

Steiger, G.H., J. Calambokidis, J.M. Straley, L.M. Herman, S. Cerchio, D.R. Salden, J. Urban-R., C.M. Gabriele, M.E. Dalheim, S. Uchida, J.K.B. Ford, P. Ladron de Guevera-P., M. Yamaguchi and J. Barlow. 2008. Geographic variation in killer whale attacks on humpback whales in the North Pacific: implications for predation pressure. Endangered Species Research, 4: 247-256.

Stephenson, R.L., K.J. Clark, M.J. Power, F.J. Fife, and G.D. Melvin. 2001. Herring stock structure, stock discreteness, and biodiversity. *In* Herring: Expectations for a new millennium, p.559-571. Edited by F. Funk, J. Blackburn, D. Hay, A.J. Paul, R. Stephenson, R. Torensen, and D. Witherell. University of Alaska Sea Grant, AK-SC-01-04, Fairbanks.

Stokes, K. and R. Law. 2000. Fishing as an evolutionary force. Marine Ecology Progress Series 208:307-309.

Stokesbury, K.D.E., J. Kirsch, E.D. Brown, G.L. Thomas, and B.L. Norcross. 2000. Spatial distributions of Pacific herring, *Clupea pallasi*, and walleye pollock, *Theragra chalcogramma*, in Prince William Sound, Alaska. Fishery Bulletin 98:400–409.

Stokesbury, K.D.E., J. Kirsch, E.V. Patrick, and B.L. Norcross. 2002. Natural mortality estimates of juvenile Pacific herring (*Clupea pallasi*) in Prince William Sound, Alaska. Canadian Journal of Fisheries and Aquatic Science 59:416–423.

Straley, J.M.1990. Fall and Winter Occurrence of Humpback Whales (*Megaptera novaeangliae)* in Southeast Alaska. Report International Whaling Commission (Special Issue 12):319-323.

Straley, J.M. 1994. Seasonal characteristics of humpback whales (*Megaptera novaeangliae*) in southeastern Alaska. Master's thesis, University of Alaska, Fairbanks, Alaska.

Straley, J.M. 2009. Year Round Presence of Humpback Whales in Alaskan Waters and the Impact upon Pacific Herring. Gulf of Alaska – Pacific Herring Workshop, Alaska Marine Science Symposium, Jan. 2009.

Straley, J., C. Gabriele and C.S. Baker. 1995. Seasonal Characteristics of Humpback Whales (*Megaptera novaeangliae*) in Southeastern Alaska. *In* Proceedings of the Third Glacier Bay Science Symposium, p 229-237. Edited by D. Engstrom. 1993 National Park Service, Anchorage , AK..

Straley, J., J. Moran, R. Heintz, L. Schaufler, K. McLaughlin, A. McLaughlin and S. Rice. 2010. Humpback Whale Predation on Pacific herring Part 3: What Do Humpback Whales Eat during the Fall and Winter in Prince William Sound? Gulf of Alaska – Mammals, Alaska Marine Science Symposium, Jan. 2010.

Sturdevant, M.V., E. Fergusson, N. Hillgruber, C. Reese, J. Orsi, R. Focht, A. Wertheimer and B. Smoker. 2011. Lack of trophic competition among wild and hatchery juvenile chum salmon during early marine residence in Taku Inlet, Southeast Alaska. Environmental Biology of Fishes [Accessed on-line 10/21/11 at http://www.springerlink.com/content/0378-1909/?k=sturdevant]

Sturdevant, M., E. Fergusson, J. Orsi, R. Brenner, and B. Heard. 2011. Salmon as predators and prey in marine waters of Alaska. Presentation at Alaska Marine Science Symposium, Anchorage, Alaska. Auke Bay Laboratories, 17109 Pt. Lena Loop Rd., Juneau, AK 99801.

Sturdevant, M.V. J. A. Orsi & E. A. Fergusson. 2012. Diets and Trophic Linkages of Epipelagic Fish Predators in Coastal Southeast Alaska during a Period of Warm and Cold Climate Years, 1997–2011, Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science, 4:1, 526-545

Sullivan, T.M., R.W. Butler, and W.S. Boyd. 2002. Seasonal distribution of waterbirds in relation to spawning Pacific herring, *Clupea pallasi*, in the Strait of Georgia, British Columbia. Canadian Field-Naturalist 116:366-370.

Sveegaard, S.,J. Nabe-Nielsen, K. Staehr, T.F.Jensen, K.N. Mouritsen and J. Teilmann.Sparial interactions between marine predators and their prey: herring abundance as a driver for the distributuions of mackerel and harbour porpoise. Marine Ecology Progress Series 468:245-253.

Swain, D.P. and E.J. Wade. 1993. Density-dependent geographic distribution of Atlantic cod (*Gadus morhua*) in the southern Gulf of St. Lawrence. Canadian Journal of Fisheries and Aquatic Science 50: 725-733.

Tanasichuk, R.W. 1997. Influence of biomass and ocean climate on the growth of Pacific herring (*Clupea pallasi*) from the southwest coast of Vancouver Island. Canadian Journal of Fisheries and Aquatic Science 54: 2782-2788.

Tanasichuk, R.W. 2000. Age-specific natural mortality rates of adult Pacific herring (*Clupea pallasi*) from southern British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 57: 2258-2266.

Tanasichuk, R.W. and D.M. Ware. 1987. Influence of interannual variations in winter sea temperature on fecundity and egg size in Pacific Herring (*Clupea harengus pallasi*). Canadian Journal of Fisheries and Aquatic Science 44: 1485–1495.

Teerlink, S., O. von Zeigesar, J. Straley and T. Quinn. 2010. Humpback Whale Predation on Pacific herring Part 1: Construction of historical time series of humpback whale abundance in Prince William Sound relative to Pacific herring dynamics.Gulf of Alaska – Mammals, Alaska Marine Science Symposium, Jan. 2010.

Teerlink, S.F., and T.J. Quinn II. (in prep) The ecological importance of humpback whale predation on herring biomass in Prince William Sound as determined by model covariation. Prepared for the Fisheries Oceanography.

Tester, A.L. 1933. Populations of herring in the coastal waters of British Columbia. Transactions of the American Fisheries Society 63:286-289.

Tester, A.L. 1955. Estimation of recruitment and natural mortality rate from age-composition and catch data in British Columbia herring populations. Journal of the Fishery Research Board of Canada 12:649-681.

Thomas, A.C., M.M. Lance, S.J. Jeffries, B.G. Miner and A. Acevedo-Gutierrez. 2011. Harbor seal foraging response to a seasonal resource pulse, spawning Pacific herring. Marine Ecology Progress Series 441: 225-239.

Thomas, G.L., and R.E. Thorne. 2001. Night-time predation by Steller sea lions. Nature 411:1013.
Thomas, G.L., and R.E. Thorne. 2003. Acoustical-optical assessment of Pacific herring and their predator assemblages in Prince William Sound, Alaska. Aquatic Living Resources 16:247–253.

Thornton, T.F., V.L. Butler, F. Funk, M.L. Moss, J. Hebert, and T. Elder. 2010a. Herring synthesis: documenting and modeling herring spawning areas within socio-ecological systems over time in the southeastern Gulf of Alaska. North Pacific Research Board Project # 728. 676 p.

Thornton, T.F., M.L. Moss, V.L. Butler, J. Hebert, and F. Funk . 2010b. Local and traditional knowledge and the historical ecology of Pacific herring in Alaska. Journal of Ecological Anthropology 14: 81-88.

Thorsteinson, F. V. 1962. Herring predation on pink salmon fry in a southeastern Alaska estuary. Transactions of the American Fisheries Society 91:321-332.

Thynes, T., W. Davidson, D. Gordon, K. Monagle, K. and S. Walker. 2010. 2010 Southeast Alaska Sac Roe herring Fishery Management Plan. ADF&G Regional Information Report No. 1J10-03. March 2010. 26 p.

Thynes, T., D. Gordon, K. Monagle and S. Walker. 2011. 2011 Southeast Alaska sac roe herring fishery management plan. ADF&G Regional Information Report No. 1J11-23. 26 p.

Thynes, T., D. Gordon, K. Monagle and S. Walker. 2012. 2012 Southeast Alaska sac roe herring fishery management plan. ADF&G Regional Information Report No. 1J12-02. 25 p.

Tjelmeland, S. and U. Lindstrom. 2005. An ecosystem element added to the assessment of Norwegian spring-spawning herring: implementing predation by minke whales. ICES Journal of Marine Science 62:285-294.

Toresen, R., and O.J. Ostvedt. 2000. Variation in abundance of Norwegian spring-spawning herring (*Clupea harengus*, Clupeidae) throughout the 20th century and the influence of climatic fluctuations. Fish and Fisheries 1:231–256.

Trites, A.W., D.G. Calkins, and A.J. Winship. 2007. Diets of Steller sea lions *(Eumetopias jubatus)* in Southeast Alaska, 1993–1999. Fishery Bulletin 105:234–248.

Trenkel, V.M., J.K. Pinnegar, M. Rochet and B.D. Rackham. 2004. Different surveys provide similar pictures of trends in a marine fish community but not of individual fish populations. ICES Journal of Marine Science 61:351-362.

Trumble, R.J. 1979. Analysis of data relating to possible effects of sac roe herring fishing on the abundance of bait herring. State of Washington Dept. of Fisheries Progress Report No. 80. 37 p.

Tsou, T.S., and J.S. Collie. 2001. Estimating predation mortality in the Georges Bank fish community. Canadian Journal of Fisheries and Aquatic Sciences 58:908–922.

Turner, S.J., S.F. Thrush, V.J. Cummings, J.E. Hewitt, M.R. Wilkinson, R.B. Williamson, and D.J. Lee. 1997. Changes in epifaunal assemblages in response to marina operations and boating activities. Marine Environmental Research 43:181–199.

Turnock, B. 2010. Assessment of the Arrowtooth Flounder Stock in the Gulf of Alaska (Executive Summary). 2010 North Pacific Groundfish Stock Assessment and Fishery Evaluation (SAFE) Report, http://www.afsc.noaa.gov/refm/stocks/assessments.htm (Accessed 1/14/2011).

Tyrell, M.C., J.S. Link, H. Moustahfid, and W.J. Overholtz. 2008. Evaluating the effect of predation mortality on forage species population dynamics in the Northeast US continental shelf ecosystem using multispecies virtual population analysis. ICES Journal of Marine Science 65:1689–1700.

University of Alaska Fairbanks. “New findings show increased ocean acidification in Alaska”, School of Fisheries and Ocean Sciences Newsletter, Fall 2009.

USAID (United States Agency for International Development). 2009. Adapting to Coastal Climate Change, A Guidebook for Development Planners. United States Agency for International Development, Global Climate Change Team, Wash. D.C.

Valentine P.C., J.S. Collie, R.N. Reid, R.G. Asch, V.G. Guida, and D.S. Blackwood. 2007. The occurrence of the colonial ascidian Didemnum sp. on Georges Bank gravel habitat – Ecological observations and potential effects on groundfish and scallop fisheries. Journal of Experimental Marine Biology and Ecology 342:179–181.

Varpe, O., O. Fiksen and A. Slotte. 2005. Meta-ecosystems and biological energy transport from ocean to coast: the ecological importance of herring migration. Oecologia 146:443-451.

Veermeer, K., M. Bentley, K.H. Morgan, and G.E.J. Smith. 1997. Association of feeding flocks of Brant and sea ducks with herring spawn at Skidegate Inlet. *In* The ecology, status, and conservation of marine and shoreline birds of the Queen Charlottes Islands, p. 102-107. Edited by Vermeer, K. and K.H. Morgan. Canadian Wildlife Service Occasional Paper No. 93

Vetter, E.F.1988. Estimation of natural mortality in fish stocks: A review. Fishery Bulletin 86: 25 – 43.

Vincent, A. and Y. Sadovy. 1998. Reproductive ecology in the conservation and management of fishes. *In* Behavioral Ecology and Conservation Biology, p. 209-245. Edited by T. Caro. Oxford University Press, New York.

Vines, C.A., T. Robbins, F.J. Griffin, and G.N. Cherr. 2000. The effects of diffusible creosote-derived compounds on development of Pacific herring (*Clupea pallasi*). Aquatic Ecology 51:225–239.

Voellenweider, J.J., J.L. Gregg, R.A. Heintz, and P.K. Hershberger. 2011b. Energetic cost of Ichthyophonus infection in juvenile Pacific herring (*Clupea pallasii*). Journal of Parasitology Research 201: 10 p.

Vollenweider, J.J., R.A. Heintz, L. Schaufler and R. Bradshaw. 2011a. Seasonal cycles in whole-body proximate composition and energy content of forage fish vary with water depth. Marine Biology 158:413-427.

Wainwright, T.C. and R.G. Kope. 1999. Methods of extinction risk assessment developed for US West Coast salmon. ICES Journal of Marine Science 56:444-448.

Walker, D.I., and G.A. Kendrick. 1998. Threat to macroalgal diversity: Marine habitat destruction and fragmentation, pollution and introduced species. Botanica Marina 41:105–112.

Walters, C.J., M. Stocker, A.V. Tyler, and S. Westrheim. 1986. Interaction between Pacific cod (*Gadus macrocephalus*) and herring (*Clupea harengus pallasi*) in the Hecate Strait, British Columbia. Canadian Journal of Fisheries and Aquatic Science 43:830–837.

Wang, M.Y., J.E. Overland and N.A. Bond. 2010. Climate projections for selected large marine ecosystems. Journal of Marine Systems 79: 258-266.

Ware, D. 1985. Life History Characteristics, Reproductive Value, and Resilience of Pacific Herring (*Clupea harangus pallasi*). Canadian Journal of Fisheries and Aquatic Science 42: 127-137.

Ware, D.M. 1991a. Climate forcing of Pacific herring recruitment and growth in Southern British Columbia. *In* Proceedings of the Seventh Annual Pacific Climate (PACLIM) Workshop, April, 1990, p. 127-130. Edited by J. Betancourt and V. Tharp. California Department of Water Resources. Interagency Ecological Studies Program Technical Report 26.

Ware, D.M. 1991b. Climate, predators and prey: behavior of a linked oscillating system. *In* Long-term Variability of Pelagic Fish Populations and Their Environment, p. 279–291. Rdited by T. Kawasaki, S. Tanaka, Y. Tova, and A. Taniguchi. Pergamon Press, Tokyo, Japan.

Ware, D.M, and G.A. McFarlane. 1989. Fisheries production domains in the Northeast Pacific Ocean. *In* Effects of ocean variability on recruitment and an evaluation of parameters used in stock assessment models, p. 359–379. Edited by R.J. Beamish and G.A. McFarlane. Canadian Special Publication Fisheries and Aquatic Science 108.

Ware, D.M. and C. Tovey. 2004. Pacific herring spawn disappearance and recolonizarion events. Fisheries and Oceans Canada Research Document 2004/008. Vancouver B.C. 48 pp.

Ware, D.M., C. Tovey, D. Hay and B. McCarter. 2000. Straying rates and stock structure of british Columbia herring. Fisheries and Oceans Canada Research Document 2000/006, Vancouver B.C. 32 pp.

Warner, R.R. and P.L.Chesson. 1985.Coexistence mediated by recruitment fluctuations: a field guide to the storage effect. American Naturalist 125:769-787.

Weingartner, T. 2007a. The physical environment of the Gulf of Alaska. *In* Long-term ecological change in the northern Gulf of Alaska, p. 12–47. Edited by R.B. Spies. Elsevier. Amsterdam.

Weingartner, T. 2007b. Climate. *In* Long-term ecological change in the northern Gulf of Alaska, p. 170–180. Edited by R.B. Spies. Elsevier. Amsterdam.

Weingartner, T.J., S. Danielson, and T.C. Royer. 2005. Freshwater variability and predictability in the Alaska Coastal Current. Deep-Sea Res. II 52:169–191.

Weinrich, M., M. Martin, R. Griffiths, J. Bove, and M. Schilling. 1997. A shift in distribution of humpback whales, *Megaptera novaeangliae*, in response to prey in the southern Gulf of Maine. Fishery Bulletin 95:826–836.

White, B. 2011. Alaska Salmon Enhancement Program 2010 Annual Report, ADF&G Fishery Management Report No. 10-05, Anchorage. 47 p.

Wildes, S. L., Vollenwieder, J. J., Nguyen, H. T., & Guyon, J. R. (2011). Genetic variation between outer-coastal and fjord populations of Pacific herring (*Clupea pallasii*) in the eastern Gulf of Alaska. Fishery Bulletin 109, 382-393.

Willette, T.M., R.T. Cooney, V. Patrick, D.M. Mason, G.L. Thomas and D. Scheel. 2001. Ecological processes influencing mortality of juvenile pink salmon (*Oncorynchus gorbuscha*) in Prince William Sound, Alaska. Fisheries Oceanography 10 (Suppl.1):14-41.

Williams, E.H. 1999. Interrelationships of Pacific herring, *Clupea pallasi*, populations and their relation to large-scale environmental and oceanographic variables. PhD Thesis. University of Alaska, Fairbanks, Alaska.

Williams, E.H. and T.J. Quinn II. 2000a. Pacific herring, *Clupea pallasi*, recruitment in the Bering Sea and north-east Pacific Ocean, I: relationships among different populations. Fisheries Oceanography 9:285–299.

Williams, E.H. and T.J. Quinn II. 2000b. Pacific herring, *Clupea pallasi*, recruitment in the Bering Sea and north-east Pacific Ocean, II: relationships to environmental variables and implications for forecasting. Fisheries Oceanography 9:300–315.

Williams, G.D., and R.M. Thom. 2001. Marine and estuarine shoreline modification issues. Washington Department of Fish and Wildlife White Paper 00-01215-009. 83 p.

Willson M.F., S.M. Gende and B.H.Marston. 1998. Fishes and the forest. BioScience 48: 455-462.

Willson, M.F. and J.N. Womble. 2006. Vertebrate exploitation of pulsed marine prey: a review and example of spawning herring. Reviews of Fish Biology and Fisheries 16:183–200.

Wilson, B. and L.M. Dill. 2002. Pacific herring respond to simulated odontocete echolocation sounds. Canadian Journal of Fisheries and Aquatic Sciences 59:542–553.

Wing, B. L. and K. Krieger. 1983. Humpback whale prey studies in southeastern Alaska, summer 1982. Unpubl. rep., 60 p. Auke Bay Laboratory, Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA, P.O. Box 210155, Auke Bay, AK 99821.

Wing, B., M. Masuda, and S. Taylor. 2006. Time series analysis of physical environment data records from Auke Bay, Alaska. NOAA Tech. Memo. NMFS-AFSC-166. Oct. 2006. 89 p.

Wing, B.L. and J.J. Pella. 1998. Time series analyses of climatological records from Auke Bay, Alaska. NOAA Technical Memorandum NMFS-AFSC-91. 104 p.

Winship, A.J., and A.W. Trites. 2003. Prey consumption of Steller sea lions (*Eumetopias jubatus)* off Alaska: How much prey do they require? Fishery Bulletin 101:147–167.

Witteveen, B.H., R.J. Foy and K.M. Wynne. 2006. The effect of predation (current and historical) by humpback whales (*Megaptera novaeangliae*) on fish abundance near Kodiak Island, Alaska. Fishery Bulletin, 104:10-20.

Witteveen, B.H., K.M. Wynne and T.J. Quinn. 2007. A feeding aggregation of humpback whales *Megaptera novaeangliae* near Kodiak Island, Alaska: historical and current abundance estimation. Alaska Fishery Research Bulletin 12:187-196.

Womble, J.N., and M.F. Sigler. 2006. Seasonal availability of abundant energy-rich prey influences the abundance and diet of a marine predator, the Steller sea lion *Eumetopias jubatus*. Marine Ecology Progress Series 325:281–293.

Womble, J., M. Sigler, and M. Willson. 2009. Linking seasonal distribution patterns with prey availability on a central-place forager, the Steller sea lion. Journal of Biogeography 36: 439–451.

Womble, J.N., M.F. Willson, M.F. Sigler, B.P. Kelly, and G.R. VanBlaricom. 2005. Distribution of Steller sea lions *Eumetopias jubatus* in relation to spring-spawning fish in Southeast Alaska. Marine Ecology Progress Series 294:271–282.

Woodby, D., Carlile, D., Siddeek, S., Funk F., Clark J. and L. Hulbert. 2005. Commercial Fisheries of Alaska. ADF&G Special Publication No. 05-09. 66 p.

Wynne, K. 2007. Guide to Marine Mammals of Alaska. Third edition, AK Sea Grant College Program, Fairbanks, AK. 75 p.

Yamamoto-Kawai, M., F.A. McLaughlin, E.C. Carmack, S. Nishino, and K. Shimada. 2009. Aragonite undersaturation in the Arctic Ocean: effects of ocean acidification and sea ice melt. Science 326:1098–1100.

Zebdi, A., and J.S. Collie. 1995. Effect of climate on herring (*Clupea pallasi*) population dynamics in the Northeast Pacific Ocean. *In* Climate change and northern fish populations, p. 277-290. Edited by R.J. Beamish. Canadian Special Publication of Fisheries and Aquatic Sciences 121.

Zheng, J., F. Funk and G. Kruse. 1993. Evaluation of Threshold Management Strategies for Pacific Herring in Alaska. Proceedings of the International Symposium on Management Strategies for Exploited Fish Populations, Alaska Sea Grant College program, AK-SG-93-02, 1993: 141-163.

Zheng, J., F. Funk, G. Kruse and R. Fagen.1996. Herring stock-recruitment relationships and recruitment patterns in the North Atlantic and Northeast Pacific oceans. Fisheries Research 26:257–277.

Ziemann, D.A., L.D. Conquest, K.W. Fulton-Bennett, and P.K. Bienfang, P.K. 1991. Interannual variability in the spring phytoplankton bloom in Auke Bay, Alaska. Marine Biology 109 (2):321-334.

Zydelis, R., and D. Esler. 2005. Response of wintering Steller's eiders to herring spawn. Waterbirds 28:344-350.

10.0 Appendix A

Abundance Trends of Managed Stocks:

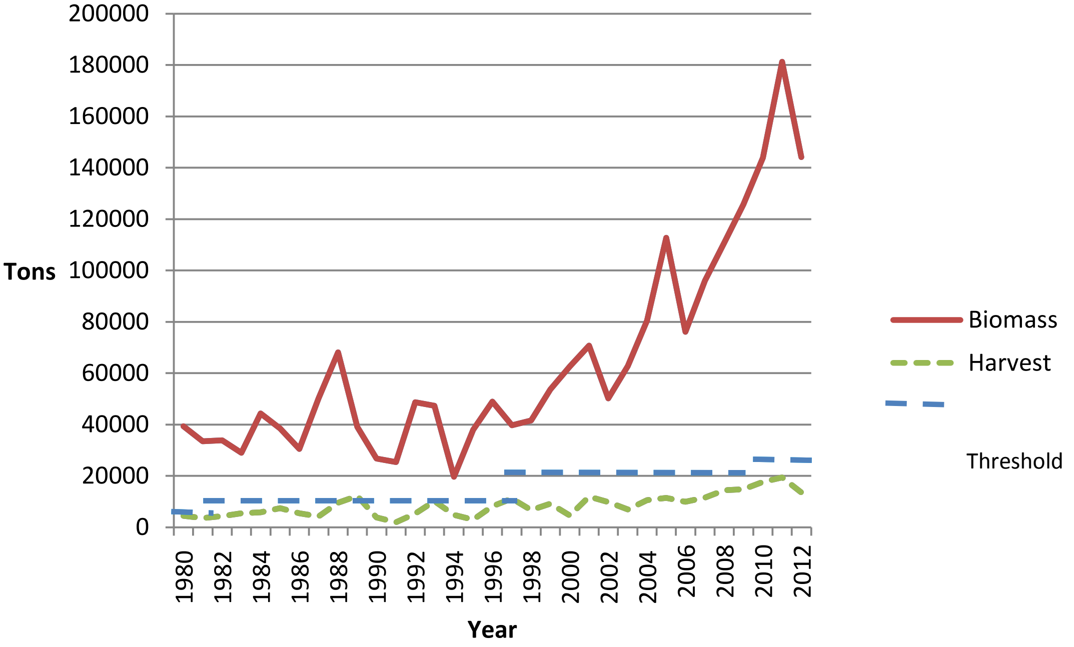


Figure A. 1. Estimated mature survey hindcast biomass, harvest, and harvest threshold for herring in Sitka Sound, 1980-2012 (Data courtesy of ADF&G).

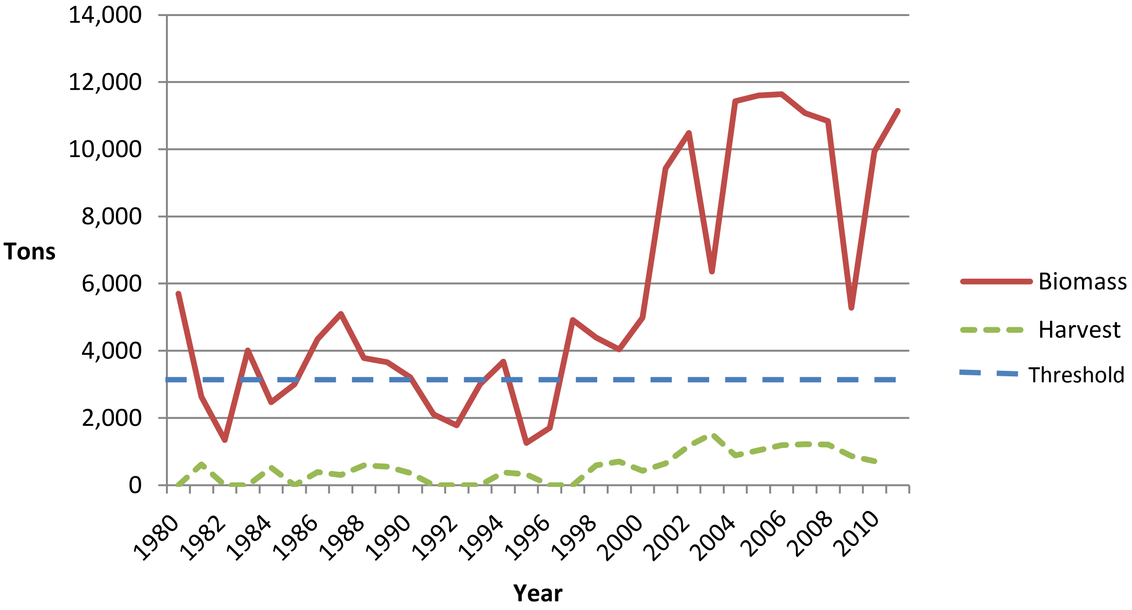


Figure A. 2. Estimated mature pre-fishery biomass, harvest, and harvest threshold for herring in Seymour Canal, 1980-2011 (Data courtesy of ADF&G).

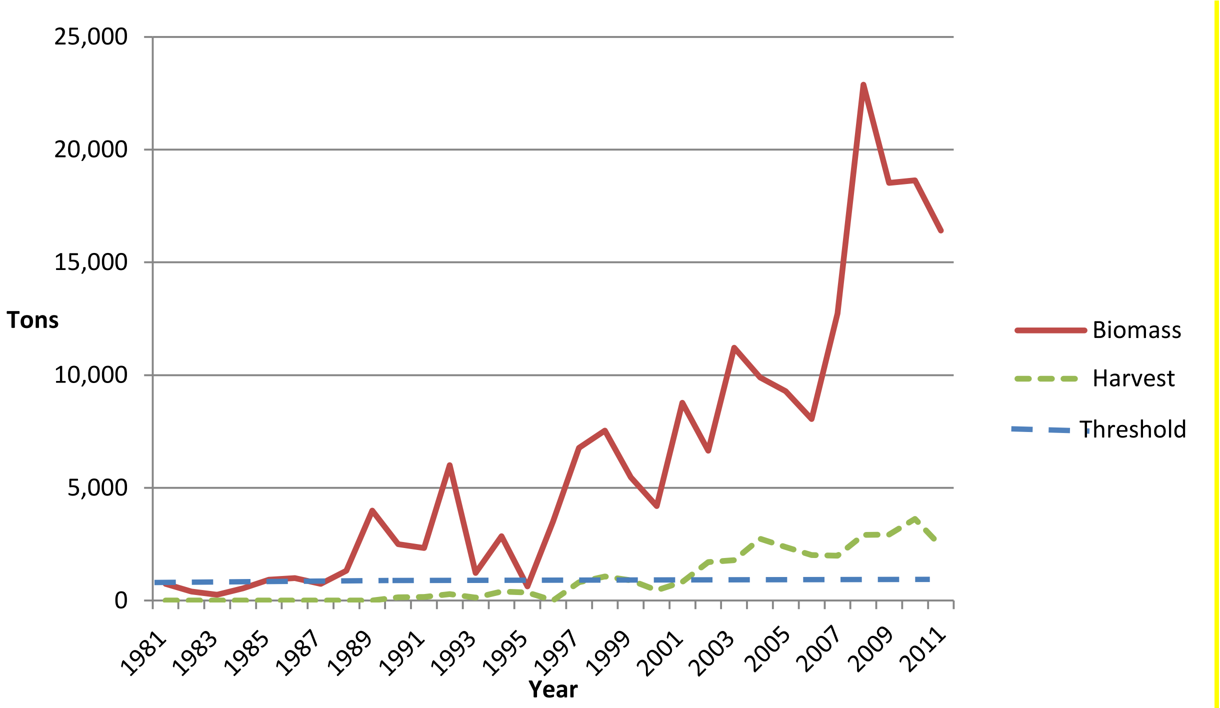


Figure A. 3. Estimated mature pre-fishery biomass, harvest, and harvest threshold for herring in Hoonah Sound, 1981-2011 (Data courtesy of ADF&G).

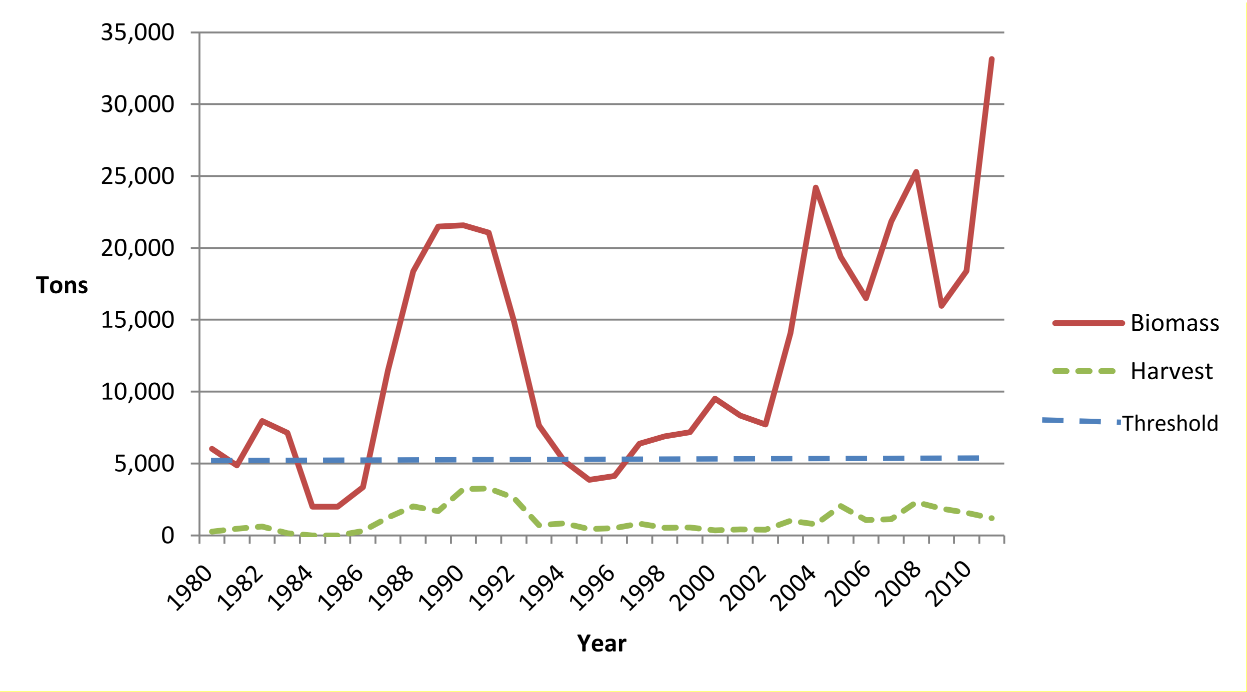


Figure A. 4. Estimated mature pre-fishery biomass, harvest, and harvest threshold for herring in Craig, 1980-2011 (Data courtesy of ADF&G).

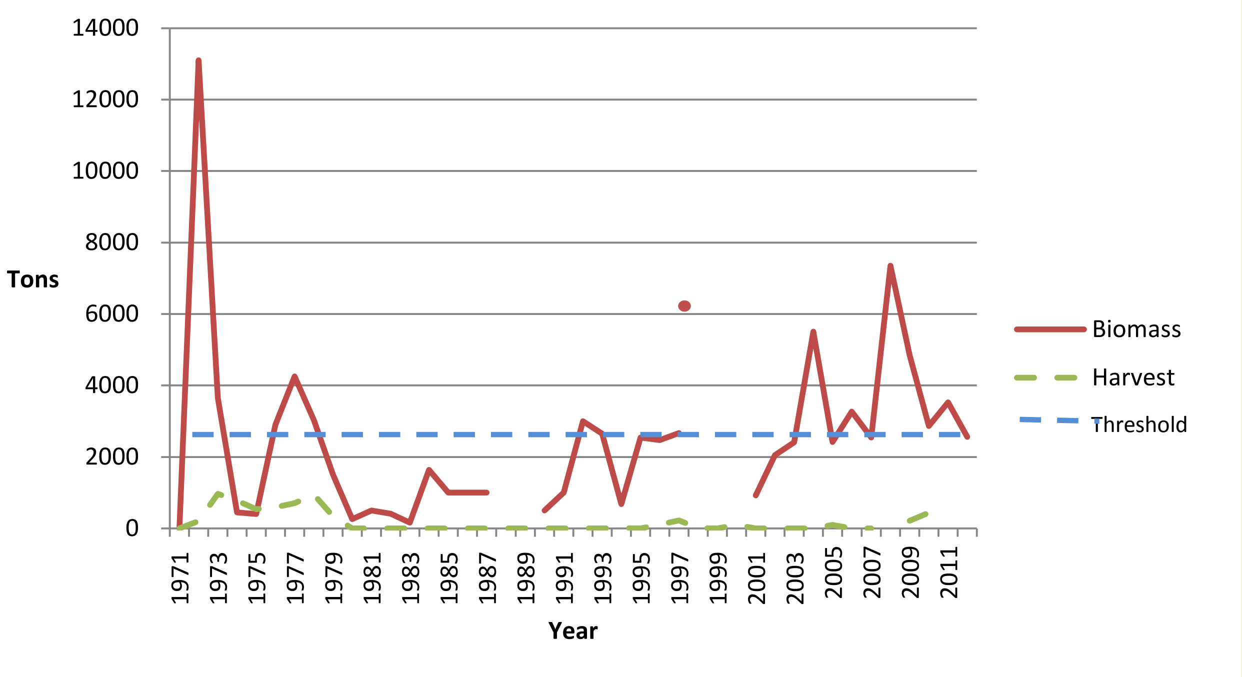


Figure A. 5. Estimated mature pre-fishery biomass, harvest, and harvest threshold for herring in Ernest Sound, 1971-2011 (Data courtesy of ADF&G).

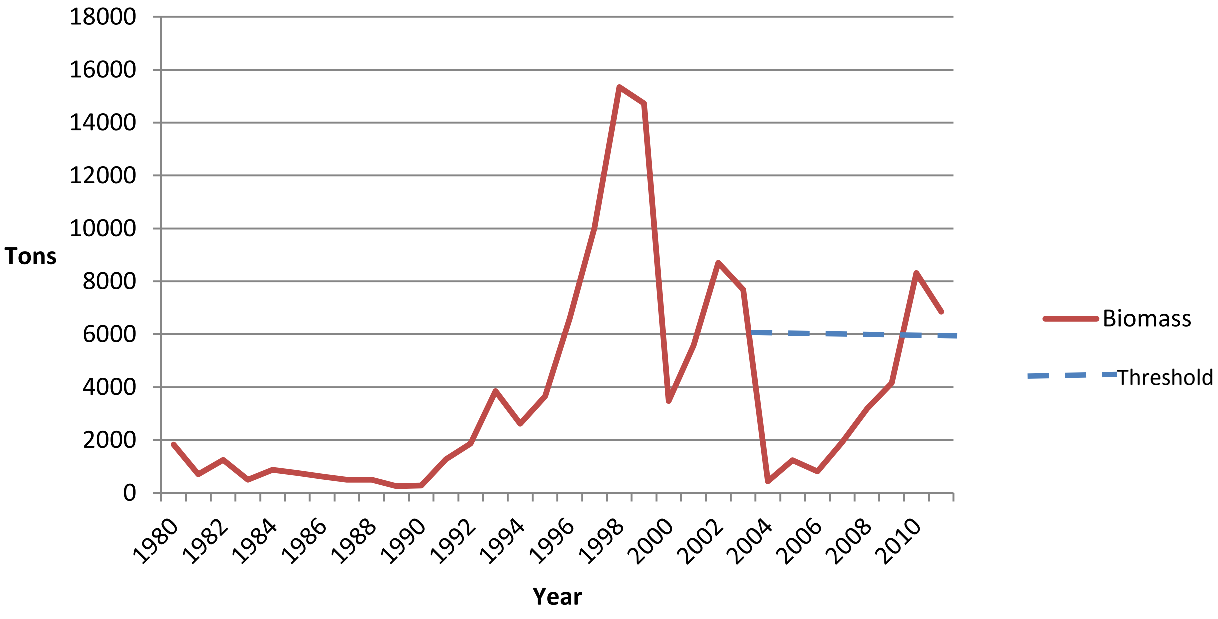


Figure A. 6. Estimated mature pre-fishery biomass, and harvest threshold for herring in West Behm, 1980-2012 (Data courtesy of ADF&G).

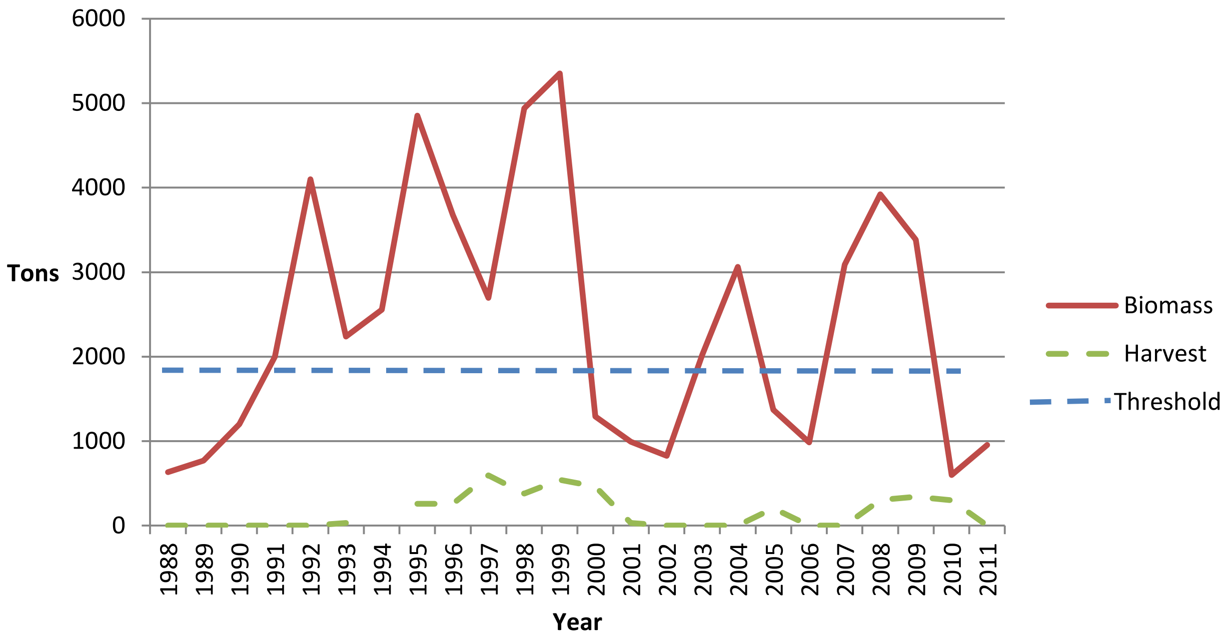


Figure A. 7. Estimated mature pre-fishery biomass, harvest, and harvest threshold for herring in the Hobart Bay/Port Houghton areas, 1988-2011 (Data courtesy of ADF&G).

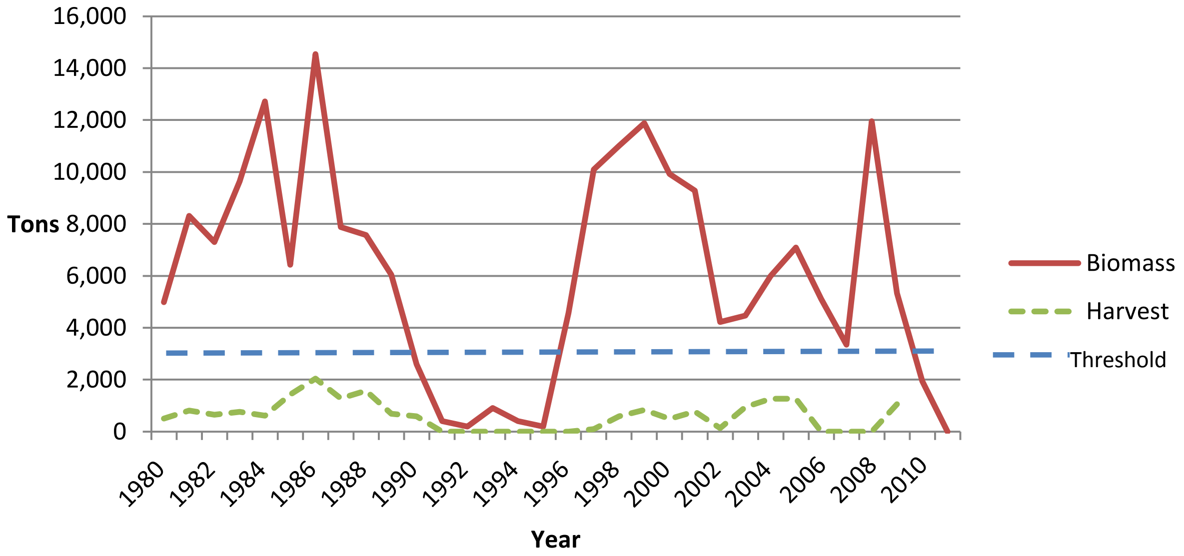


Figure A. 8. Estimated mature pre-fishery biomass, harvest and harvest threshold for herring in Tenakee Inlet, 1980-2011 (Data courtesy of ADF&G).

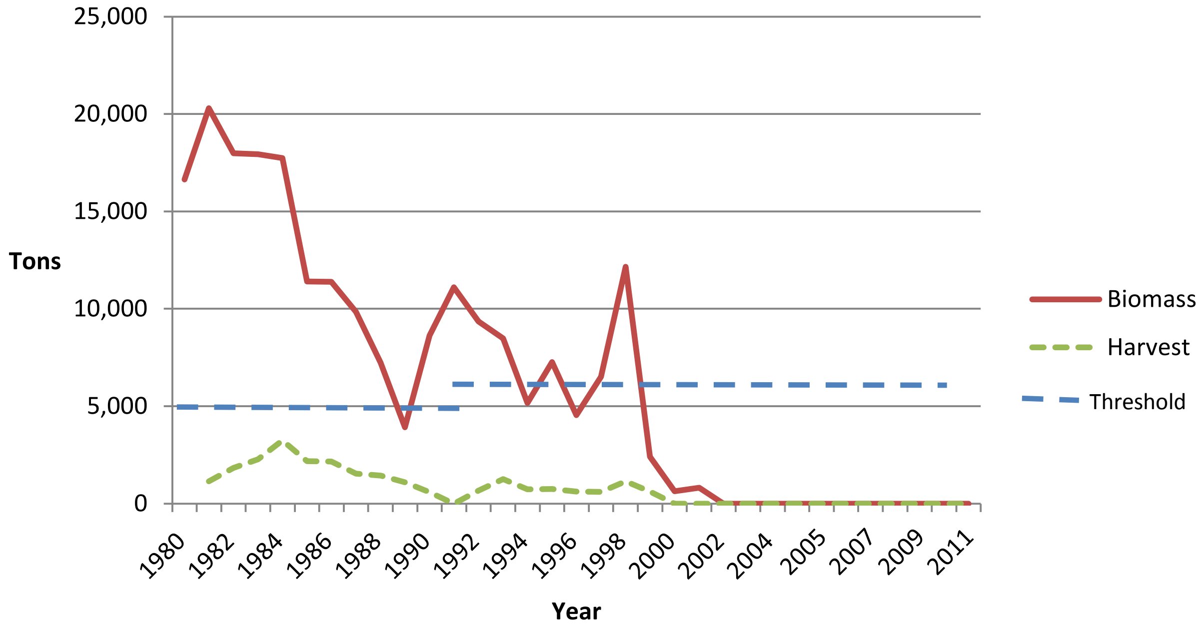


Figure A. 9. Estimated mature pre-fishery biomass, harvest, and harvest threshold for herring at Kah Shakes, 1980-2002 (Data courtesy of ADF&G).

Size-based Indicators:

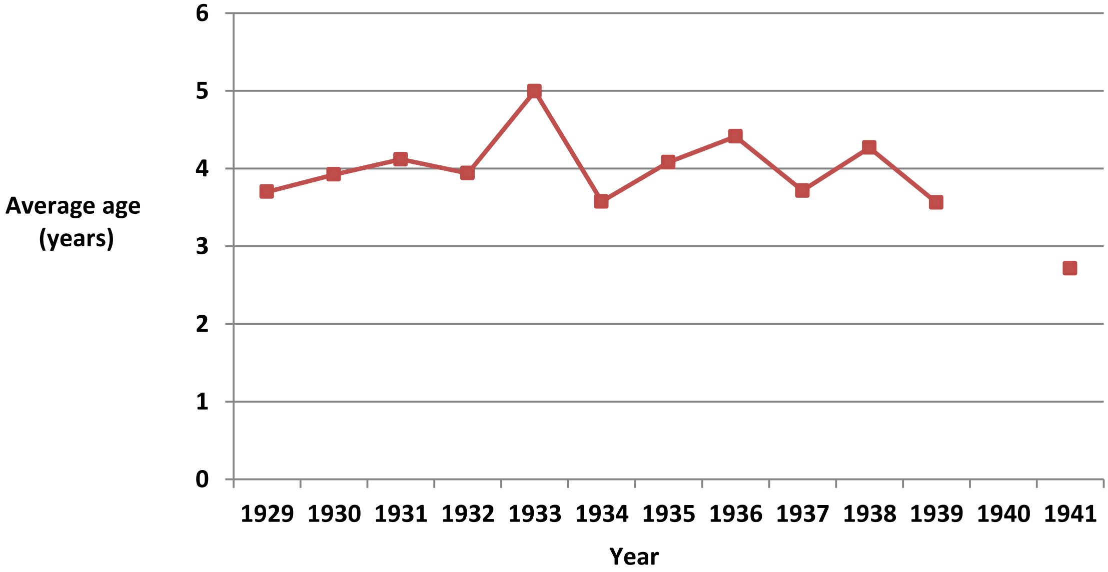


Figure A. 10. Average age of sampled fish by year during the reduction fishery, 1929-1941 (Reid 1971).

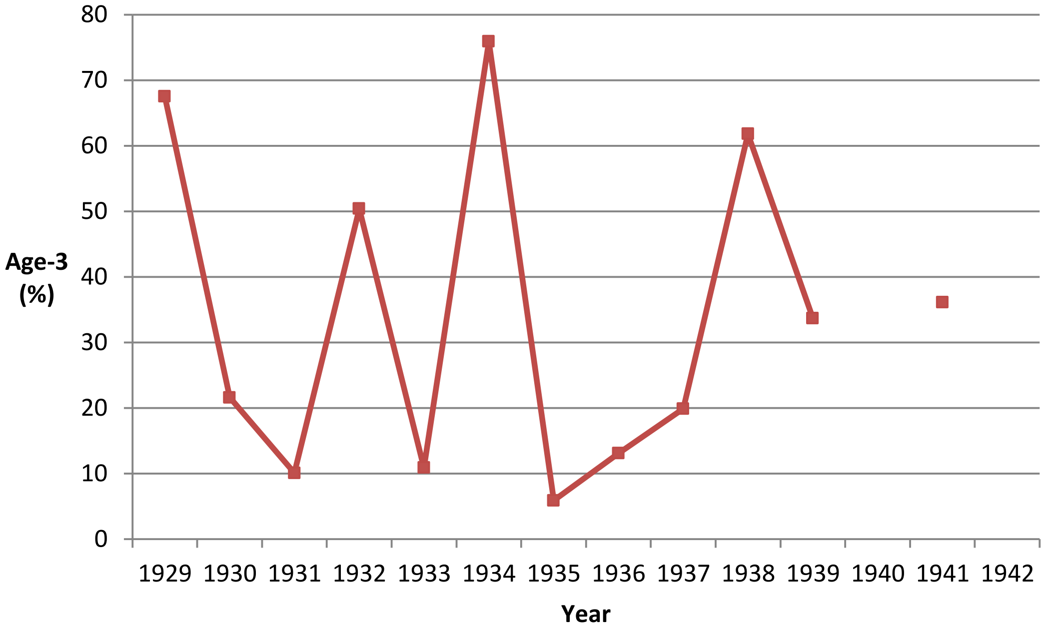


Figure A. 11. Contribution of age-3 fish to herring sampled fish from the reduction fishery, 1929-1939 (Reid 1971).

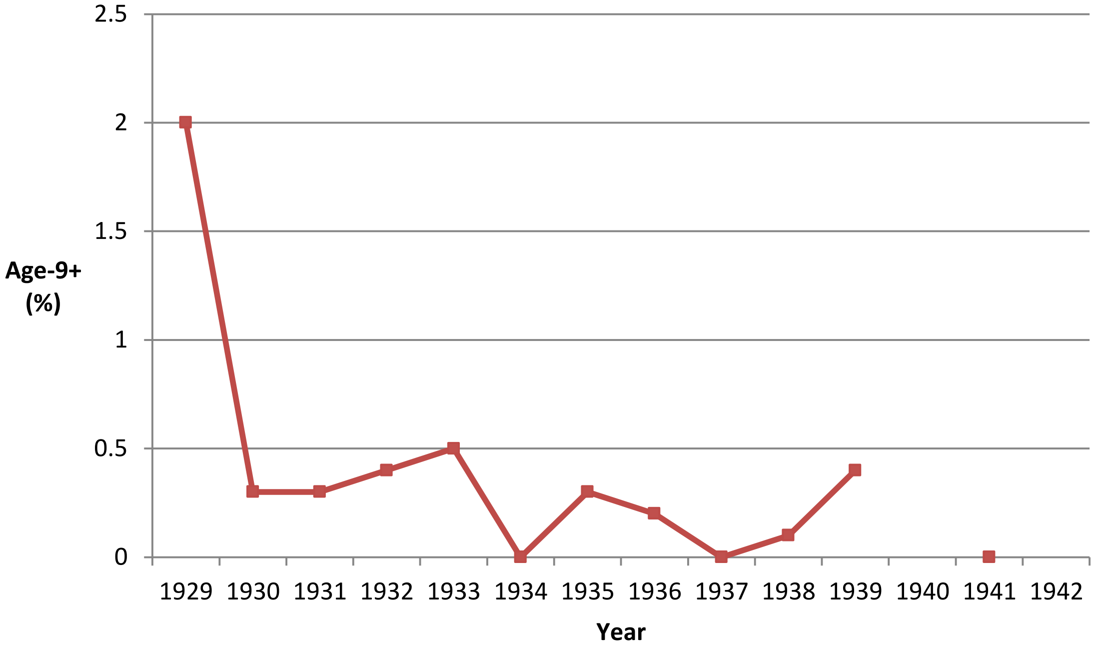


Figure A. 12. Contribution of age-9+ fish to herring sampled fish from the reduction fishery, 1929-1941 (Reid 1971).

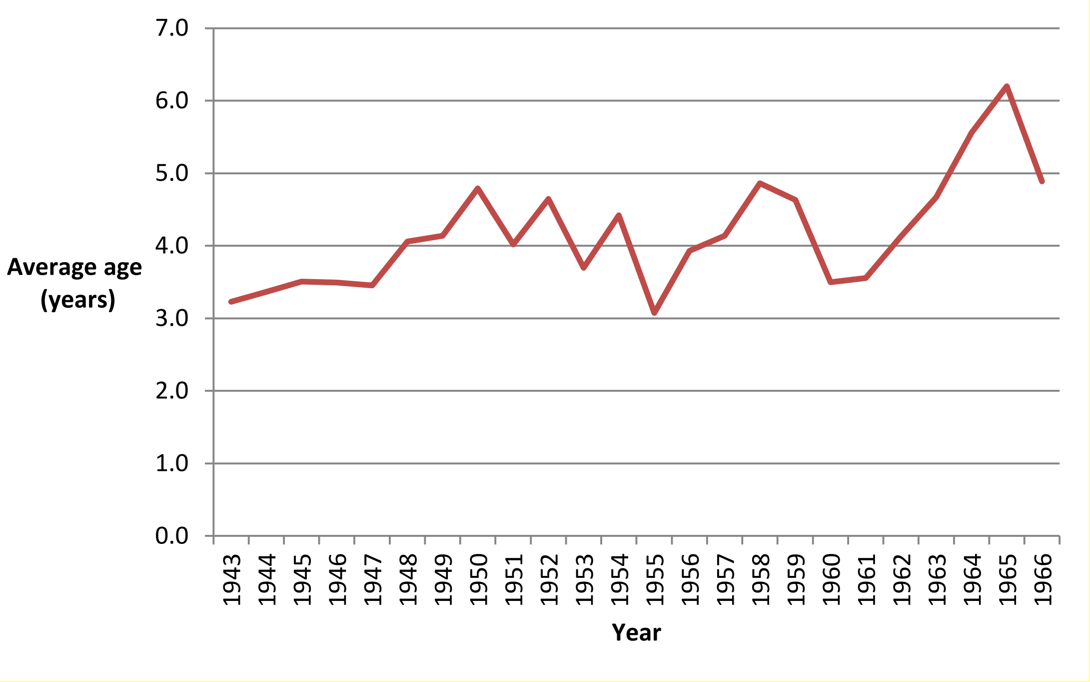


Figure A. 13. Average age by year of herring sampled from the reduction fishery, 1943-1966 (Reid 1971).

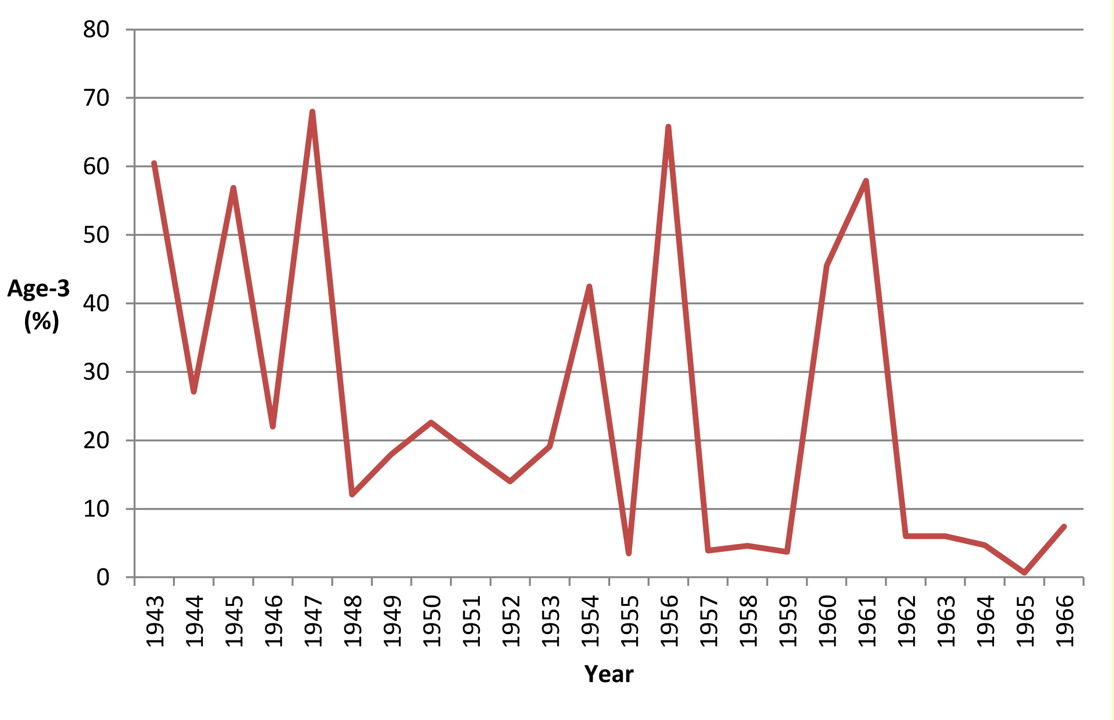


Figure A. 14. Contribution of age-3 fish to herring sampled fish from the reduction fishery, 1943-1966 (Reid 1971).

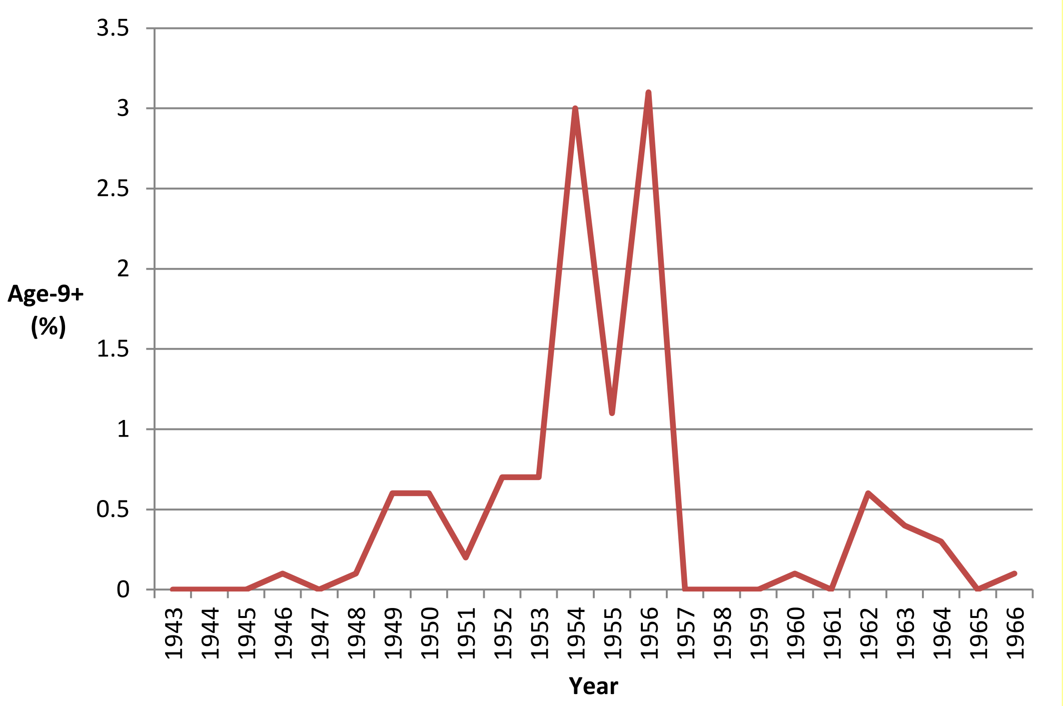


Figure A. 15. Contribution of age-9+ fish to herring sampled fish from the reduction fishery, 1943-1966 (Reid 1971).

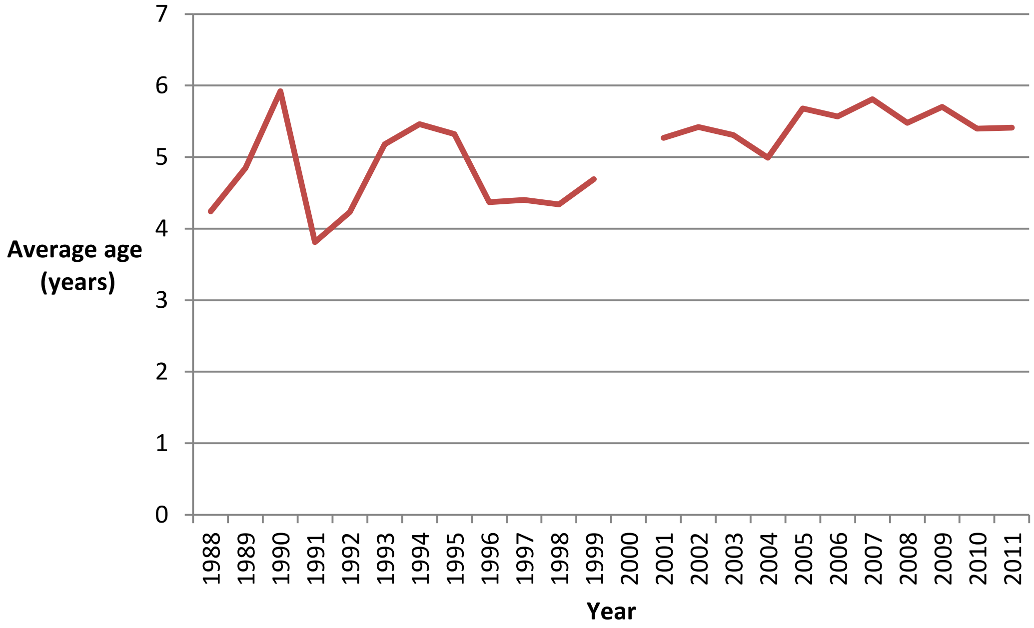


Figure A. 16. Average age of herring sampled from Sitka Sound spawning population, 1988-2011 (Data courtesy of ADF&G).

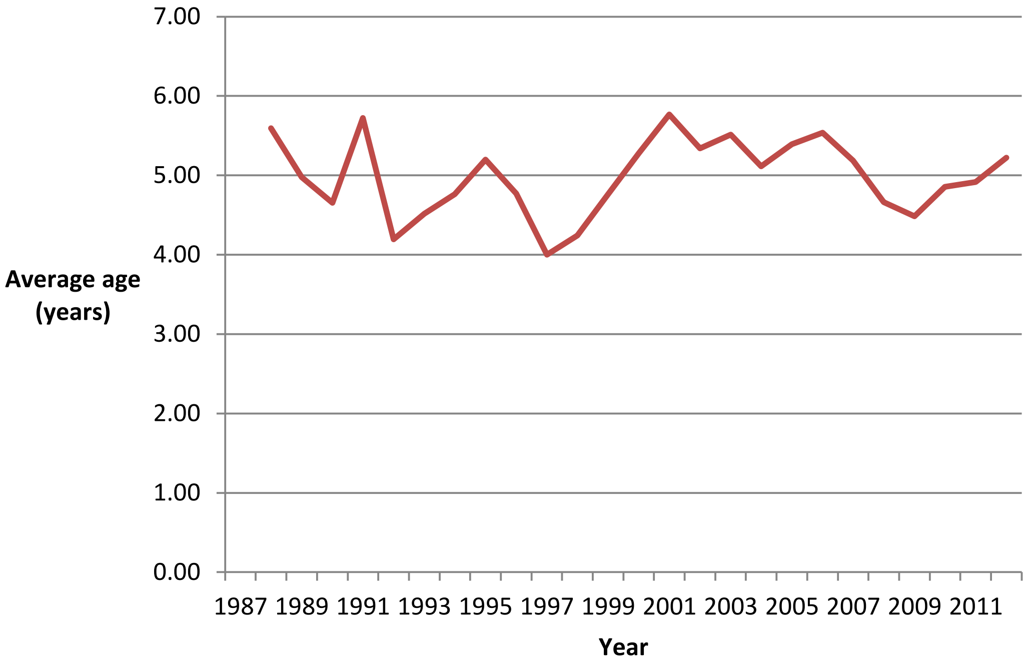


Figure A. 17. Average age of herring sampled from Lynn Canal and the eight managed stock spawning populations, excluding Sitka Sound, 1987-2011 (Data courtesy of ADF&G).

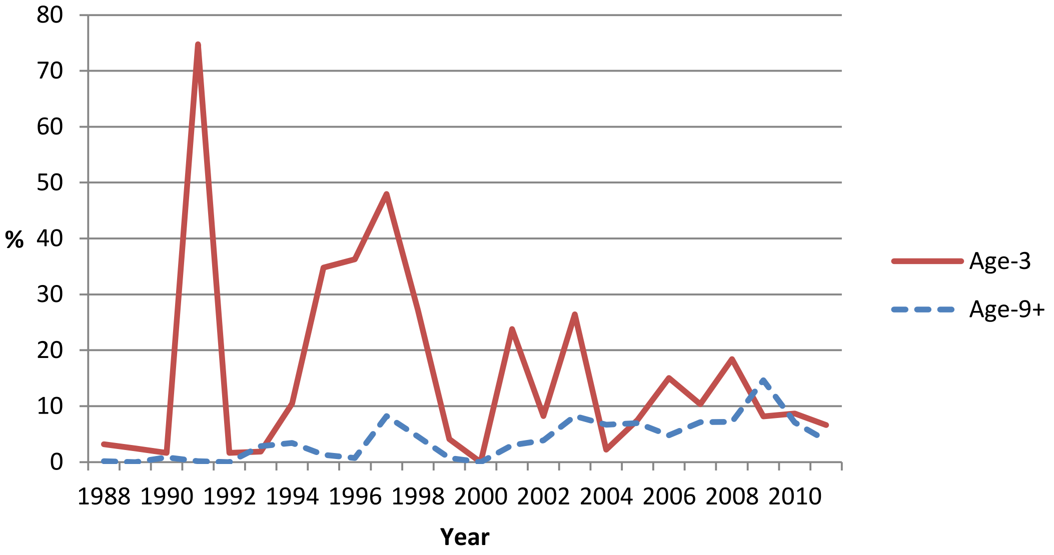


Figure A. 18. Contribution of age-3 and age-9+ fish to herring sampled from Sitka Sound spawning population, 1988-2011 (Data courtesy of ADF&G).

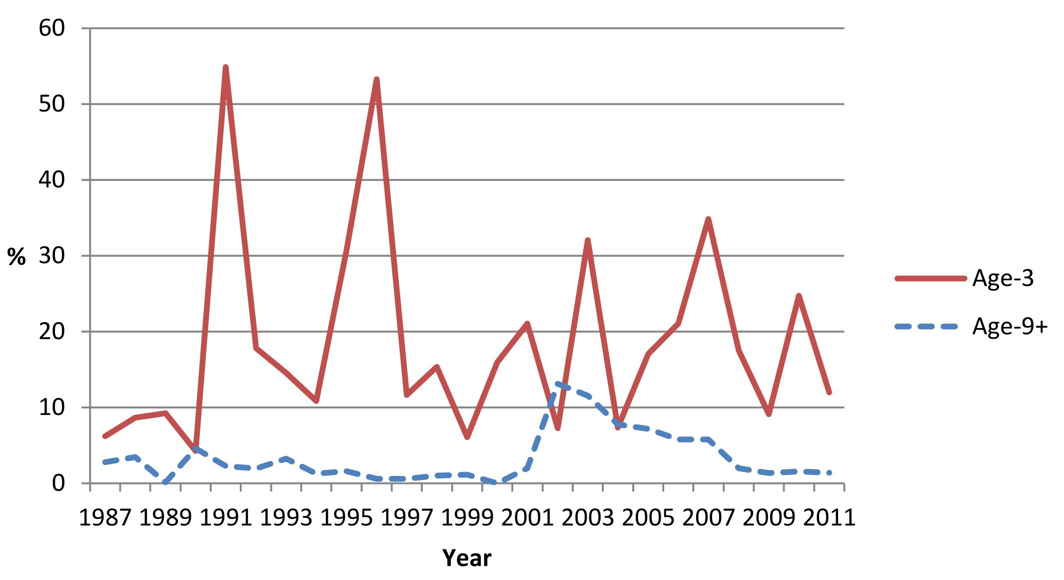


Figure A. 19. Contribution of age-3 and age-9+ fish in herring sampled from Lynn Canal and the eight managed stock spawning populations, excluding Sitka Sound, 1987-2011 (Data courtesy of ADF&G).

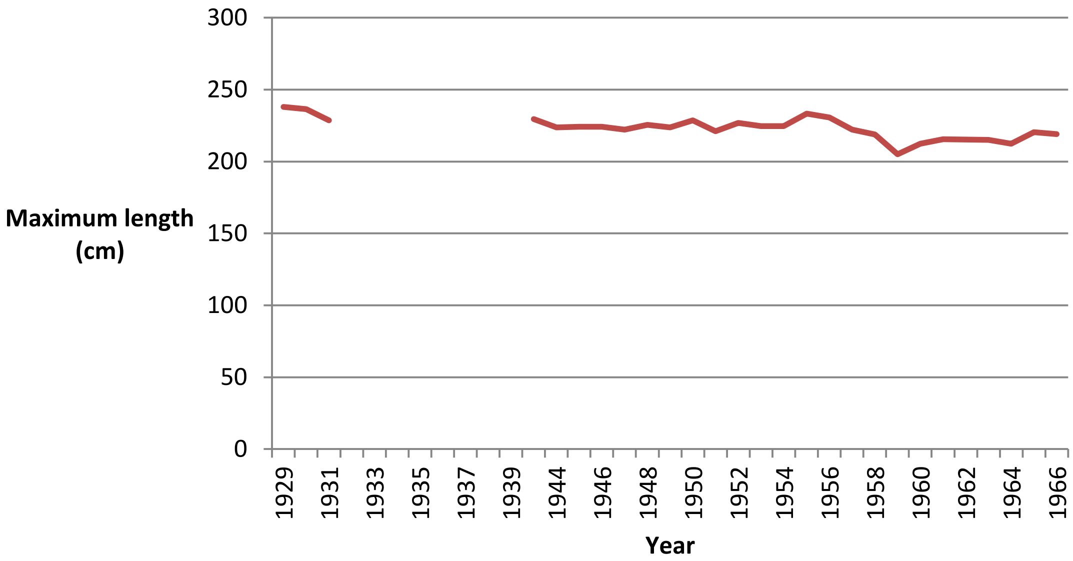


Figure A. 20. Maximum length of herring sampled from the reduction fishery, 1929-1966 (Reid 1971).

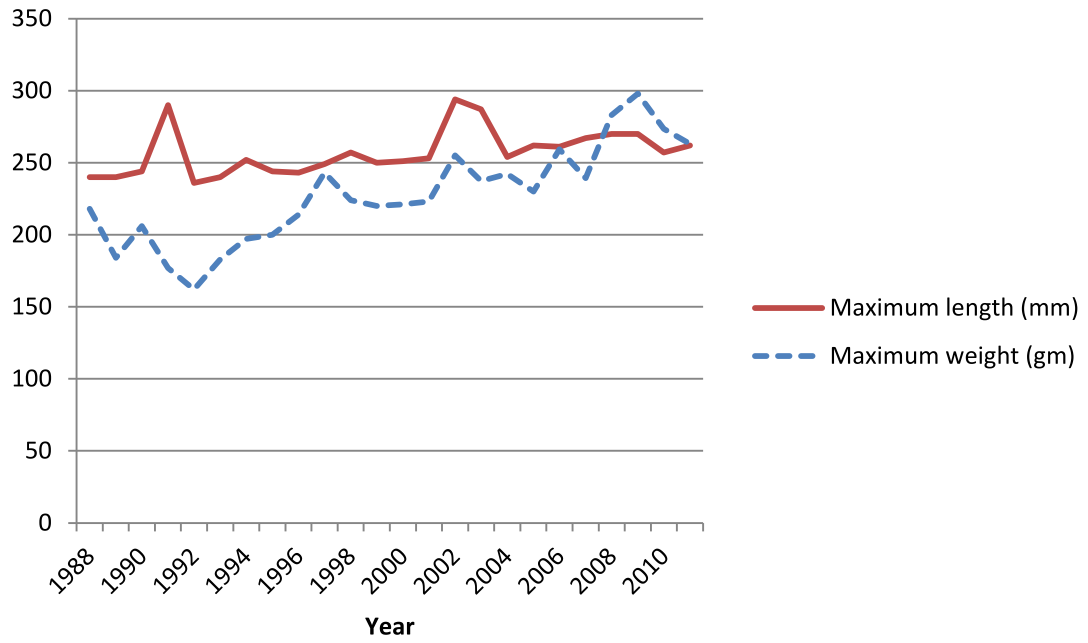


Figure A. 21. Maximum length and weight of fish sampled from Sitka Sound spawning population, 1988-2011 (Data courtesy of ADF&G).

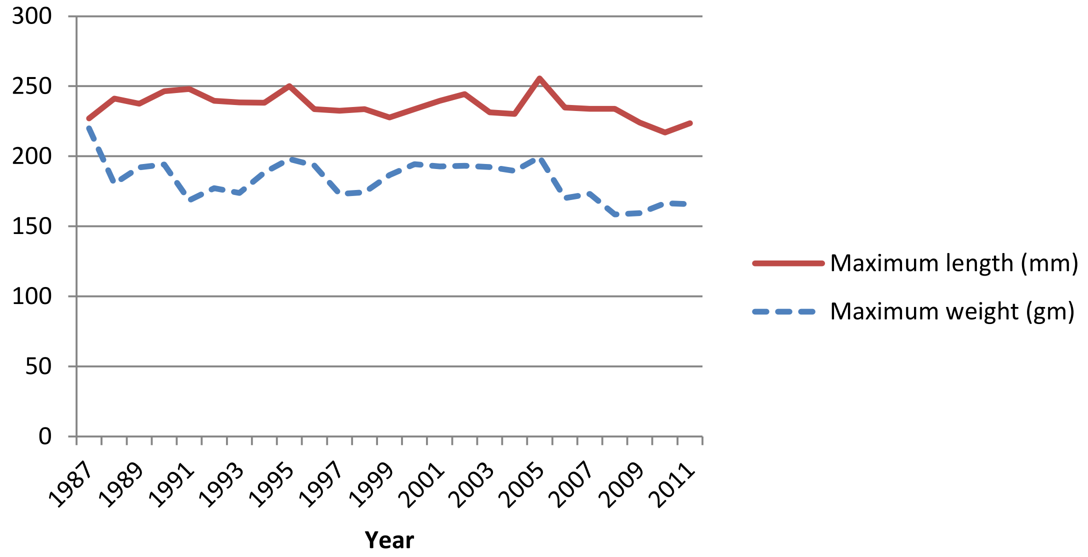


Figure A. 22. Maximum length and weight of fish sampled from Lynn Canal and the eight managed stock spawning populations, excluding Sitka Sound, 1987-2011 (Data courtesy of ADF&G).

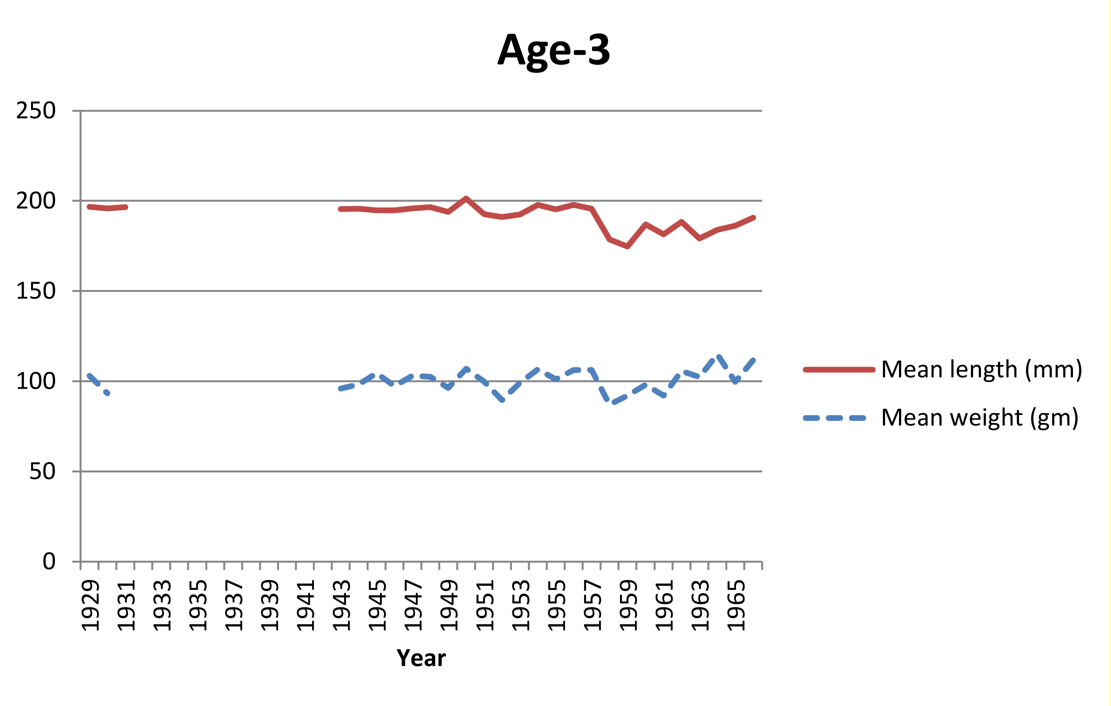


Figure A. 23. Mean body length and weight of age-3 sampled herring during the reduction fishery in Southeast Alaska, 1929-1966 (Reid 1971).

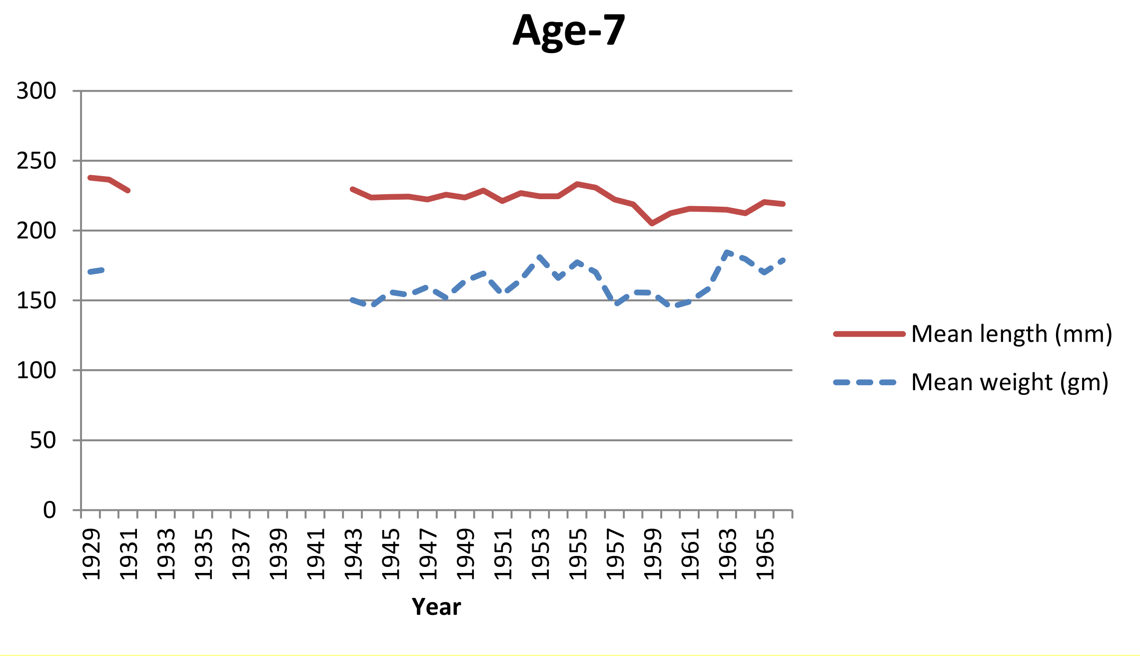


Figure A. 24. Mean body length and weight of age-7 sampled herring during the reduction fishery in Southeast Alaska, 1929-1966 (Reid 1971)

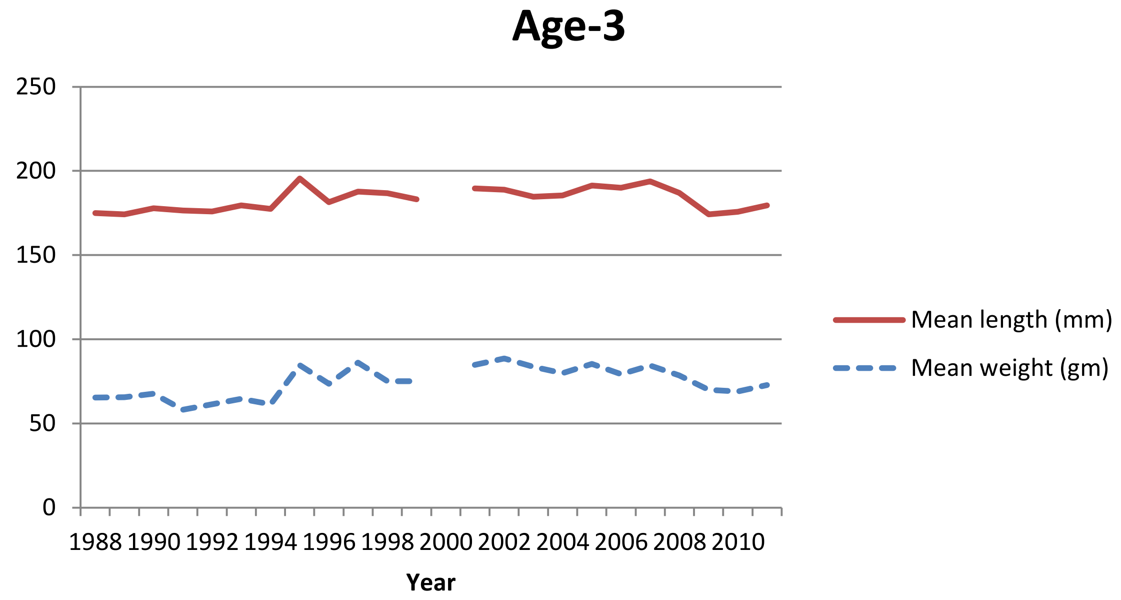


Figure A. 25. Mean body length and weight of age-3 herring sampled from Sitka Sound spawning population, 1988-2011 (Data courtesy of ADF&G).

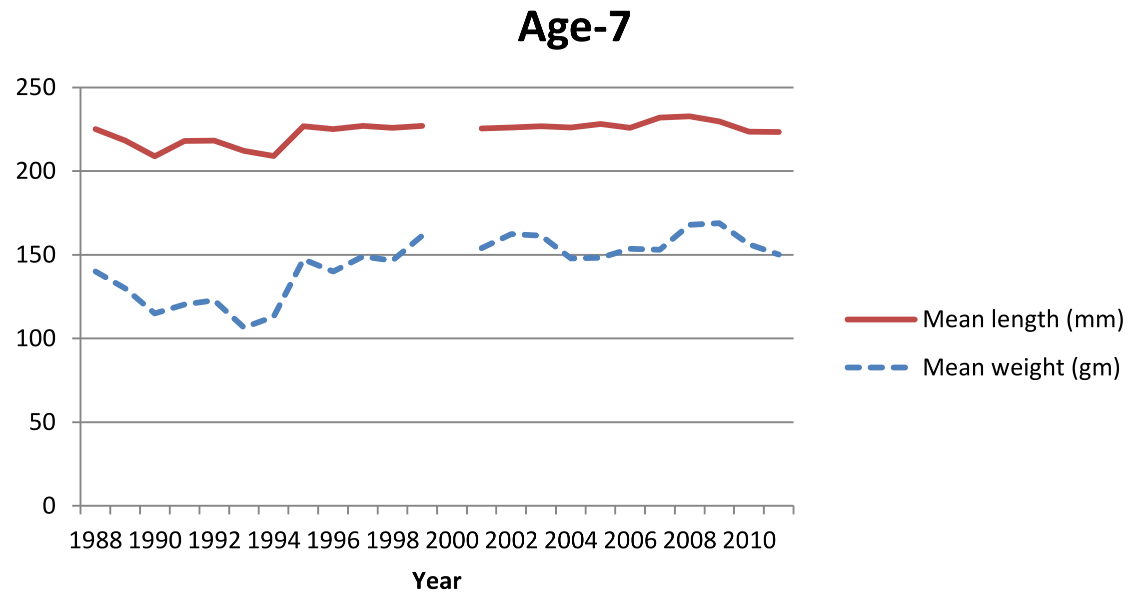


Figure A. 26. Mean body length and weight of age-7 herring sampled from Sitka Sound spawning population, 1988-2011 (Data courtesy of ADF&G).

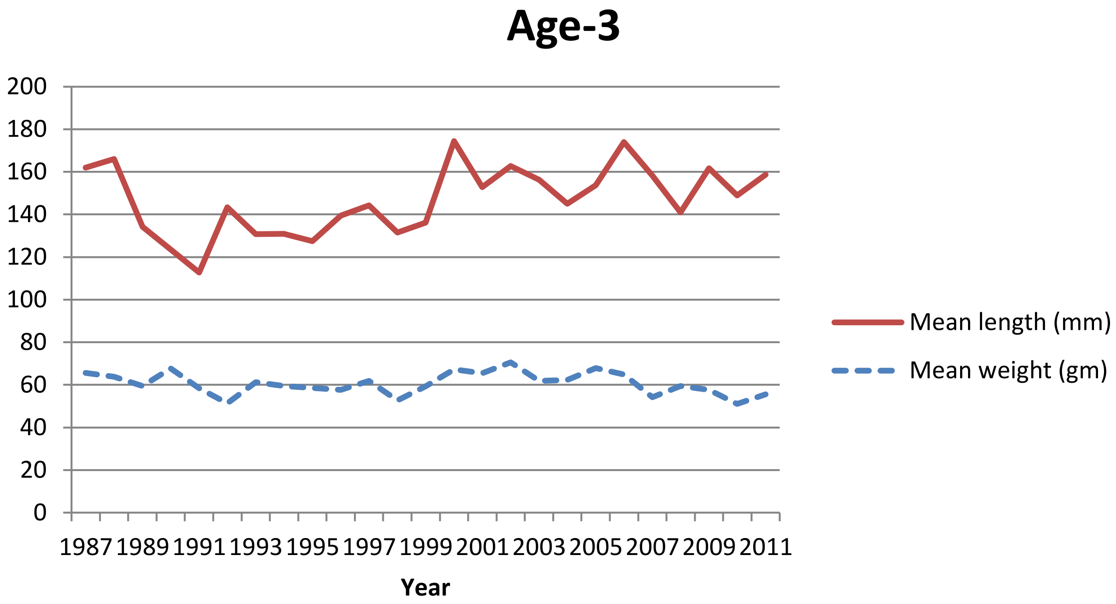


Figure A. 27. Mean body length and weight of age-3 herring sampled from Lynn Canal and the eight managed stock spawning populations, excluding Sitka Sound, 1987-2011 (Data courtesy of ADF&G).

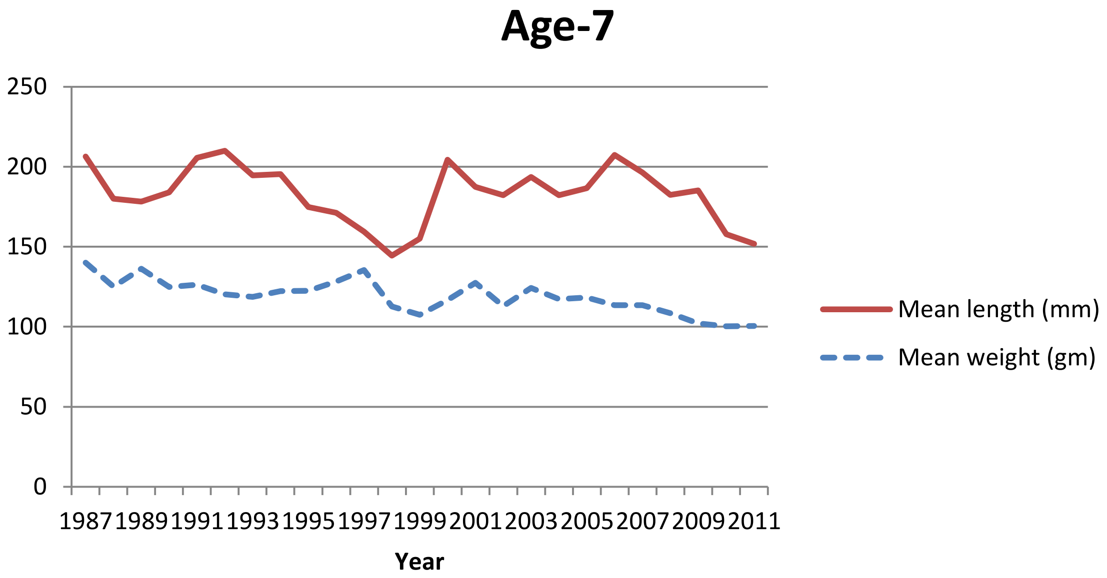


Figure A. 28. Mean body length and weight of age-7 herring sampled from Lynn Canal and the eight managed stock spawning populations, excluding Sitka Sound, 1987-2011 (Data courtesy of ADF&G).

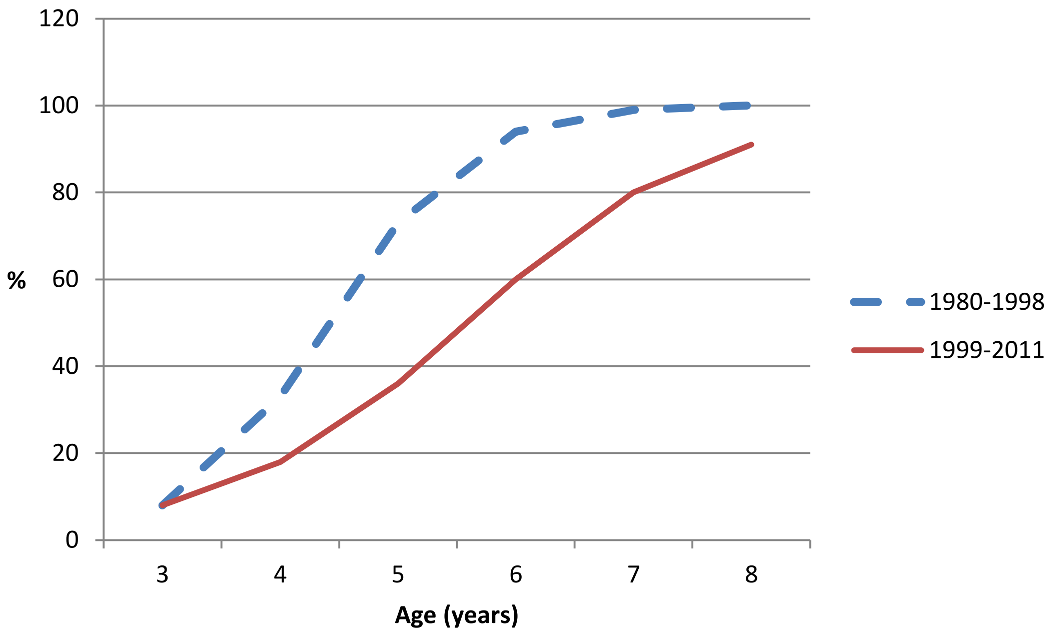


Figure A. 29. Proportions mature fish of each age class from Seymour Canal during two periods, 1980–1998 and 1999–2011, as estimated with an age structured model (Data courtesy of ADF&G).

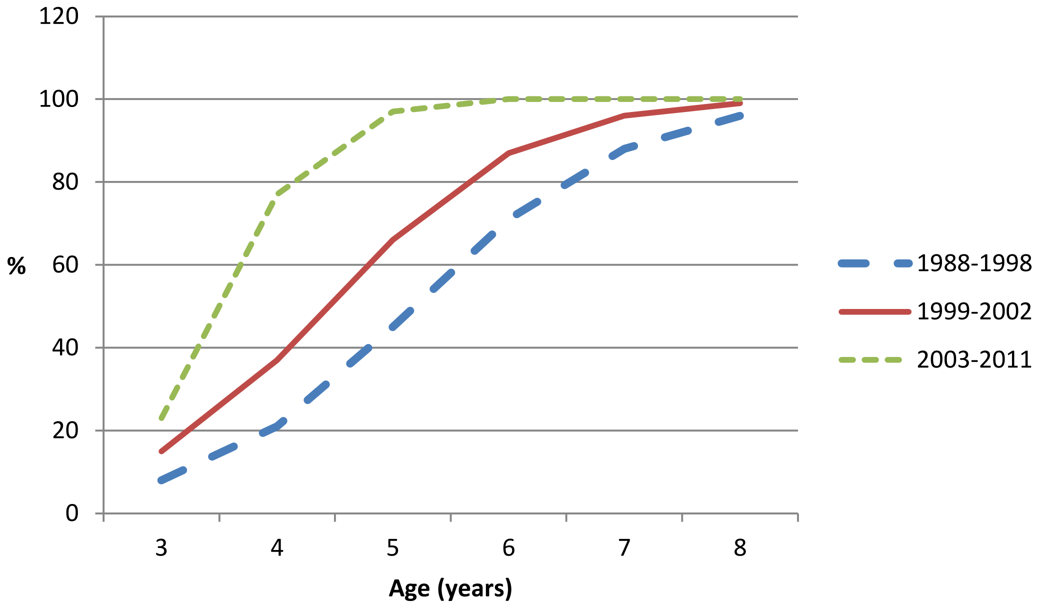


Figure A. 30. Proportions of mature fish from each age class from Craig during the periods 1988–1998, 1999–2002, and 2003–2011, as estimated with an age structured model (Data courtesy of ADF&G).